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# MHD Oxidant Intermediate Temperature Ceramic Heater Study

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TEMPERATURE CERAMIC HEATER STUDY Final  
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A. W. Carlson and I. L. Chait  
Burns and Roe, Inc.

and

D. P. Saari and C. L. Marksberry  
FluidDyne Engineering Corp.

**September 1981**

Prepared for  
National Aeronautics and Space Administration  
Lewis Research Center  
Under Contract DEN 3-107

for  
**U.S. DEPARTMENT OF ENERGY**  
**Fossil Energy**  
**Office of Magnetohydrodynamics**





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**MHD Oxidant Intermediate  
Temperature Ceramic  
Heater Study**

A. W. Carlson and I. L. Chait  
Burns and Roe, Inc.  
Woodbury, New York 11797

and

D. P. Saari and C. L. Marksberry  
Fluidyne Engineering Corp.  
Minneapolis, Minnesota 55422

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### Burns and Roe, Inc. - Prime Contractor

Mr. I.L. Chait, Project Manager  
Dr. A.W. Carlson, Project Engineer  
Mr. R.D. Rogali

### Fluidyne Engineering Corp. - Subcontractor

Mr. D.G. DeCoursin, Project Manager  
Dr. D.P. Saari, Project Engineer  
Mr. C.L. Marksberry  
Mr. F.W. Larsen  
Mr. B.C. Lindahl  
Mr. L.H. Zacho  
Mr. S.W. Holmberg  
Mr. J.E. Fenstermacher, Jr.

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# CONTENTS

	<u>Page</u>
1.0 INTRODUCTION	1
1.1 Background	1
1.2 Objectives and Scope	2
2.0 FIXED BED REGENERATIVE HEATER SYSTEM	4
2.1 Design Considerations	4
2.2 Conceptual Design	7
2.2.1 Heater System Configuration	9
2.2.2 Design Approach	16
2.2.3 Heater System Operation and Performance	25
2.3 Cost Estimate	36
2.3.1 Basis for Cost Estimate	38
2.3.2 Steel Components	39
2.3.3 Refractory Materials	40
2.3.4 Refractory Installation	40
2.3.5 Sequencing Valves	40
2.3.6 Expansion Joints	42
2.3.7 Additional Allowances	42
3.0 CERAMIC RECUPERATIVE HEATER SYSTEM	43
3.1 Design Considerations	43
3.1.1 Design Considerations for MHD Application	43
3.1.2 Review of Current Applications and Development Programs	44
3.2 Conceptual Design	47
3.2.1 Heater System Configuration	47
3.2.2 Design Approach	56
3.2.3 Heater System Operation and Performance	59
3.3 Cost Estimate	60
3.3.1 Basis for Cost Estimate	60
3.3.2 Steel Components	62
3.3.3 Refractory Materials	62
3.3.4 Refractory Installation	64
3.3.5 Silicon Carbide Assemblies	64
3.3.6 Expansion Joints	65
3.3.7 Erection and Assembly	65

## CONTENTS (Cont'd)

	<u>Page</u>
4.0 ENGINEERING ASSESSMENT OF MOVING BED REGENERATIVE HEATER	66
4.1 Moving Bed Heater Applications	66
4.2 Engineering Assessment	70
4.2.1 Advantages	70
4.2.2 Disadvantages	73
4.2.3 Significant Design Considerations	76
4.3 Areas for Further Investigation	82
5.0 HEATER SYSTEM MODIFICATIONS DUE TO LIQUID PARTICULATE MATTER IN MHD GAS STREAM	83
5.1 Design Considerations for Liquid Particulate Matter	83
5.2 Qualitative Heater System Changes	85
5.2.1 Fixed Bed Regenerative Heater	85
5.2.2 Ceramic Recuperative Heater	88
5.2.3 Moving Bed Regenerative Heater	91
6.0 TECHNICAL AND ECONOMIC COMPARISON OF ALTERNATIVES	93
6.1 Technology Status of Heater Concepts	93
6.1.1 Fixed Bed Regenerative Heater System	93
6.1.2 Ceramic Tube Recuperative Heater System	93
6.1.3 Moving Bed Regenerative Heater System	94
6.2 Performance of Heater Systems	94
6.3 Reliability and Maintenance of Heater Systems	96
6.3.1 Fixed Bed Regenerative Heater System	96
6.3.2 Ceramic Tube Recuperative Heater System	96
6.3.3 Moving Bed Regenerative Heater System	97
6.4 Effects of Liquid Particulate Matter	97
6.5 Cost Estimates	98
7.0 CONCLUSIONS	102
8.0 RECOMMENDATIONS FOR FURTHER INVESTIGATIONS	103

## CONTENTS (Cont'd)

	<u>Page</u>
<u>REFERENCES</u>	105
APPENDIX A - SPECIFICATIONS FOR MHD OXIDANT INTERMEDIATE TEMPERATURE CERAMIC HEATER SYSTEMS	113
APPENDIX B - TEMPERATURE RANGE FOR SOLID STATE OF PARTICULATE MATTER IN AN MHD EXHAUST GAS STREAM	129
APPENDIX C - SIMPLIFIED MATHEMATICAL MODEL OF PARTICLE SOLIDIFICATION IN AN MHD GAS STREAM	141
APPENDIX D - COST ESTIMATE FOR FIXED BED REGENERATIVE HEATER SYSTEM	153
APPENDIX E - COST ESTIMATE FOR CERAMIC RECUPERATIVE HEATER SYSTEM	177

## 1.0 Introduction

### 1.1 Background

High combustion temperatures are required to produce the conducting plasma for coal-fired MHD generators. The required combustion temperatures can be obtained by enriching the combustion air with oxygen or by preheating the combustion air to a temperature of 1640 K (2500 F) or greater in a high temperature air heater. High temperature air pre-heating appears to be the more efficient approach. However, oxygen enrichment of the combustion air, in conjunction with a more moderate preheat temperature, has been identified in several recent conceptual design studies, as a technically and economically viable concept for use in demonstration facilities and potential early commercial power plants (refs. 1-3). The use of oxygen enrichment is expected to accelerate development of the MHD combustor, channel, and radiant boiler and help to provide reliable MHD technology within a reasonable time frame, while development of the high temperature air heater is expected to provide the advanced technology to allow second generation MHD plants to achieve their full potential.

Conceptual designs of the MHD Engineering Test Facility (ref. 1) and of potential early commercial MHD power plants (refs. 2 and 3) were based on the use of metallic tubular heat exchangers, fired directly by the MHD exhaust gas, to pre-heat the enriched combustion air. The preheat temperature was limited to 870 K (1100 F) for the ETF study and to 920 K (1200 F) in the early commercial plant studies. The operating temperature of the heat exchanger metals is limited by the highly corrosive MHD gas, which contains coal ash and potassium compounds. Early results on metal corrosion in the MHD gas stream (ref. 4) indicated that temperatures as low as 700K (800 F) may be required to achieve satisfactory corrosion resistance. Thus, the use of directly fired metallic heat exchangers for preheating the oxygen enriched combustion air may result in a relatively low temperature limit and a correspondingly reduced overall plant efficiency.

It has been proposed that ceramic heat exchangers could be used to increase pre-heat temperature in early commercial plants to 1600°F or higher, with the heaters conservatively designed to minimize the risk of operational problems. Although ceramics are capable of withstanding very high material temperatures,

liquid coal ash and liquid seed compounds entrained in the MHD gas stream present considerable operational problems for high temperature heaters, such as those proposed for advanced 2400°F preheat plants.

A more conservative ceramic heater design approach for early commercial plants (utilizing oxygen-enriched air) would be to limit the MHD exhaust gas temperature at the heater inlet to the fusion temperature of the compound in the gas stream with the lowest melting point. The heaters would then be exposed to solid particles only. Presumably, heater operational problems would be reduced and fabrication costs would be less than they would be for high temperature heaters exposed to liquid particulates. The power plant efficiency would be higher for a plant using ceramic heaters than for a plant using metallic heaters because of the higher preheat temperatures attainable with ceramic heaters.

## 1.2 Objectives and Scope

The purpose of this study was to investigate the use of directly fired ceramic oxidant heaters which would be capable of producing a higher preheat temperature than metallic heaters, with the preheat temperature limited to the intermediate range. The specifications for the heater systems (i.e., flow rates, gas compositions, pressures, and temperatures) were specified by NASA, except for the MHD gas inlet temperature. (These specifications are presented in Appendix A.) The initial phase of this study, which was conducted by Burns and Roe, Inc., was to establish the temperature range in which the entrained particulate matter of a coal-fired MHD exhaust-gas stream would be solid. The results of this initial investigation are presented in Appendixes B and C. On the basis of this initial investigation, 1294°K (1870°F) was established as the MHD gas inlet temperature to be specified for the conceptual design work in the second phase of this study.

For the second phase of this study, conceptual designs and cost estimates were to be prepared for a fixed-bed regenerative heater system and a ceramic-tube recuperative heater system under conditions for which the particulate matter in the MHD gas stream is in the form of a dry powder. An engineering assessment was also to be conducted for a moving-bed regenerative heater system under the same set of conditions. This conceptual design work, cost estimating and engi-



neering assessment was performed by Fluidyne Engineering Corporation under sub-contract to Burns and Roe, Inc. Fluidyne also conducted a qualitative investigation to assess the changes in the design and operation of each of the three types of heater systems under conditions in which the particulate matter in the MHD gas stream entering the heater system would be in the liquid form. The results of the work conducted by Fluidyne are presented in sections 2.0 through 5.0 and Appendixes D and E of this report.

The final phase of this study was a technical and economic comparison of the alternative heater concepts. This was conducted by Burns and Roe, Inc. and is presented in section 6.0. The major conclusions of the study are summarized in section 7.0. Section 8.0 includes a brief discussion of future investigations recommended by Burns and Roe based upon the results of this investigation.

## 2.0 FIXED BED REGENERATIVE HEATER SYSTEM

The major design considerations for a fixed bed regenerative heater for the MHD intermediate temperature oxidant heater application are discussed below, followed by the conceptual design and cost estimate. The presented conceptual design does not represent an optimized heater system, since the level of effort required for optimization was beyond the scope of this study. It is felt, however, that the design and construction of a fixed bed regenerative heater for this application can be accomplished with presently available industrial materials and technology. Somewhat different choices of materials and construction techniques may result from more detailed studies at the preliminary and final design levels, but the basic heater system as presented below represents a reasonable design at the conceptual level.

### 2.1 Design Considerations

The conditions for a fixed bed, periodic flow, ceramic brick regenerative heater system for intermediate temperature oxidant heater service represent significantly less severe service than would be experienced by a directly fired high temperature air heater. The material and gas temperature levels for the intermediate temperature MHD oxidant heater are also lower than in conventional blast furnace stove systems. Therefore, the conceptual design conforms to blast furnace stove design practice with appropriate differences to accommodate the unique MHD oxidant heater requirements. Information on blast furnace stove practice was obtained from Refs. 5 and 6 and from Andco Technical Services, Inc., the U.S. licensee of the West German firm of Martin and Pagenstecher.

Major differences between this application and the blast furnace stove exist due primarily to the large particulate loading in the MHD gas stream as well as different control capabilities and needs. The lack of individual combustors, such as exist on blast furnace stoves, and the need to make more frequent load changes in a power plant than in a blast furnace make the control problem somewhat different. The pressure difference between the oxidant and the MHD exhaust gas is comparable to the maximum presently encountered in some modern blast furnace stove installations.

Since the particulate matter in the MHD exhaust gas will consist primarily of material condensed from the vapor phase, a fume of very small particles will be present. Measurements made by FluidDyne of potassium sulfate condensed from the vapor phase showed an average particle size of approximately 0.3  $\mu$ m (Ref. 7). Calculations of seed and slag particle size have also predicted predominantly submicron particle sizes in the downstream components of MHD system (Refs. 8-11). Slag particle size measurements in a MHD channel (Ref. 12) showed that particles which are not vaporized in the channel had diameters on the order of 1-2  $\mu$ m. Thus, all particles present in the MHD gas stream are expected to be smaller than 1-2  $\mu$ m. The particles are assumed to be in a dry (i.e. non-sticky) form through the entire heater system.

The large particulate loading requires that erosion resistant materials be used for duct liners and for refractory checkers. Based on a review of erosion concerns, it was determined that low cost materials suitable for the temperature service and having adequate erosion resistance are available for the MHD application.

Much information is available on erosion of materials by particles entrained in gas flows. Erosion has been studied and tested for various applications since the 1940's, including coal fired boilers (fly ash erosion), catalytic crackers in the petrochemical industry, pneumatic solids conveying, dust ingestion in gas turbines, fluidized bed combustors, gas turbines for pressurized fluidized bed combustion applications, and coal gasification and liquefaction. Several pertinent articles on erosion were reviewed (Refs. 13-24).

Most of the available erosion information is for metals rather than ceramic materials. In general, ductile materials have been shown to have a maximum erosion rate for impingement angles of 20-30°, while brittle materials have a maximum for an impingement angle of 90°. However, refractory materials may exhibit erosion behavior typical of ductile materials at high temperature, where plastic deformation influences the erosion rate (Ref. 17). Thus, care must be taken in interpreting the results of erosion work for a particular ceramic materials application.

Erosion tests have shown a threshold particle energy below which measurable erosion has not occurred. This threshold generally occurs at velocities <200

ft/sec. and particle sizes  $\leq 20 \mu\text{m}$  (Ref. 16). Other tests have also shown that particles smaller than 5-10  $\mu\text{m}$  do not contribute significantly to erosion (Refs. 13-15). Erosion rates measured for refractory materials at temperatures up to 1200 K (1700 F) in a pneumatic conveying test showed that inexpensive refractory materials can have a high degree of erosion resistance, particularly phosphate bonded alumina materials (Ref. 20).

The materials selected for duct liners and heater matrix materials are expected to have sufficient erosion resistance due to the small particle sizes. Experience with low cost refractory materials in fluidized bed combustors (in which the particle sizes are much larger but the velocities are lower) also supports this conclusion. Fluidyne's test work with fluidized bed combustors operating at temperatures up to 1170 K (1650 F) has indicated that erosion of the refractory insulation in fluidized beds is not a problem. Erosion problems with metallic tubes immersed in fluidized beds has been reported (Ref. 21), but refractory insulation erosion has not been observed.

A second design consideration related to the particulate loading is the potential for accumulation of particulate matter in ducts, valves, and heater flow passages. Since the particulate matter will enter the heater in a dry form and will consist predominately of small particles, it is felt that the particles will remain entrained in the gas stream at the velocities determined for operation of the heater system. Thus, no special provision are made in the conceptual design to deal with fallout and deposition of particulate matter in the heater system.

The pressure difference between oxidant and MHD exhaust gas will require that flow sequencing valves withstand pressures typical of the maximum level for modern hot blast valves. The heaters will also have to be pressurized and depressurized as part of each heater cycle, necessitating additional valves for this purpose as are used in blast furnace stoves. Pressurization and depressurization valves are included in the cost estimate, but they are not shown in the accompanying figures. Some of the heater valves must also cope with particulate matter in the gas stream. These concerns were considered in the selection and sizing of valves, and allowance for particulate matter was made in calculating leakage through the heater sequencing valves.

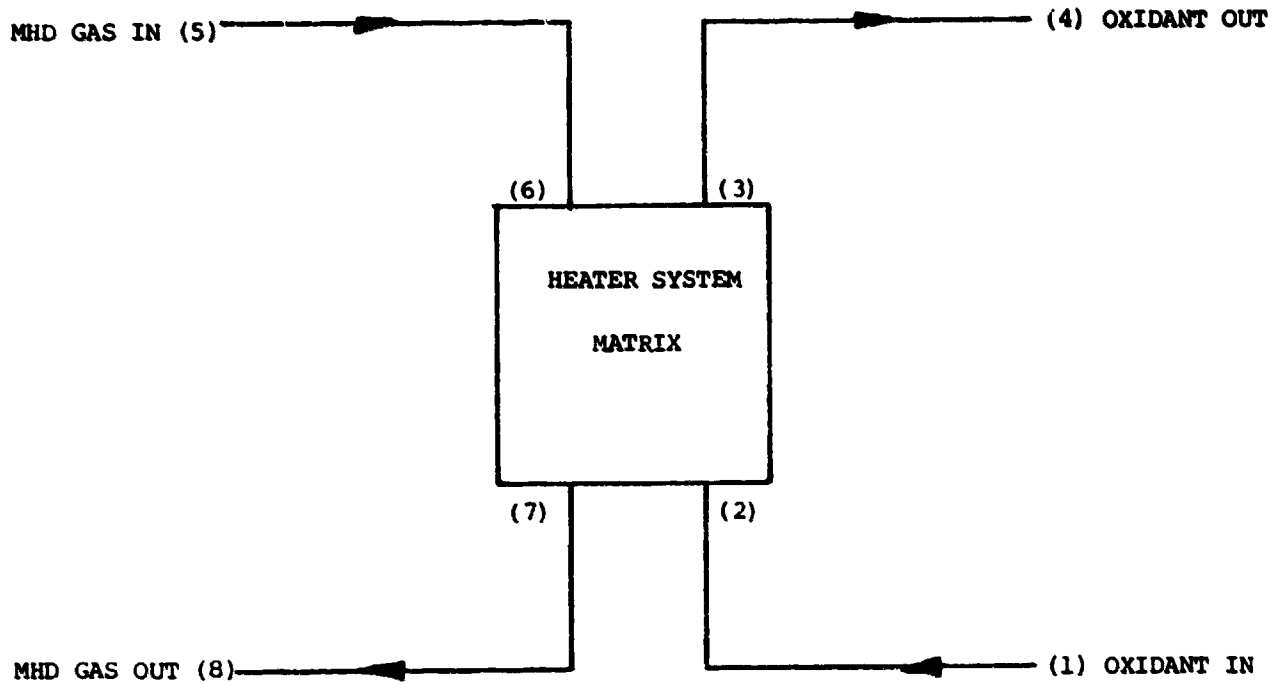
Consideration must also be given to control of the flow and temperature of the oxidant leaving the heater system. Blast furnace stove control systems achieve uniform hot blast temperatures through a combination of control of the staging of the individual stoves, control of the individual stove combustor flows and temperatures, and mixing of the hot blast stream with cooler air to moderate temperature "droop" which is inherent to periodic flow, regenerative type heaters. (Droop is the decrease in fluid outlet temperature from a single heater in a system of regenerative heaters during the periodic heating or cooling phases.) Some modern blast furnace systems operate with 4-stove systems in an operational mode referred to as staggered parallel control. These systems are computer controlled to maintain a constant hot blast temperature. The constant temperature is obtained by mixing the exiting heated air from 2 stoves. The exit temperature for one of the stoves will be higher than the required hot blast temperature and for the other it will be lower. As the exit temperature for the hotter stove decreases, the amount of flow through the cooler stove is decreased. When the exit temperature for the hotter stove is approximately the same as the required hot blast temperature, the flow through the cooler stove will have reached zero, and another stove will be brought on blast. In addition to the computer control, it is necessary that flow control valves be utilized in the inlet air streams so that flow rates through the heat exchangers can be varied as required to obtain the proper mix to maintain a constant hot blast temperature.

Similar control concepts are envisioned for this application, with the exception that variation of the MHD gas and oxidant flows to the individual heaters during a heater cycle would not be anticipated. The valves required for the MHD application are not flow control valves; these valves are gate valves which are either fully open or fully closed. Control system hardware was not included in the conceptual design, but the manifolds and ducts were sized in order to minimize maldistribution of flows among the individual heaters. An allowance for instrumentation and control equipment was made in the cost estimate.

## 2.2 Fixed Bed Regenerative Heater System Conceptual Design

The heater system process diagram is shown in Figure 1. The oxidant inlet and outlet temperatures, the MHD gas inlet temperature, the oxidant flow rate out of

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Section Number	Fluid	Flow		Temperature		Location
		kg/sec	(lbm/sec)	K	(F)	
1	Oxidant	234.4	(516.3)	513	(463)	Entering heater system
2	Oxidant	233.9	(515.2)	511	(460)	Entering bottom of matrix
3	Oxidant	233.9	(515.2)	1147	(1605)	Leaving top-of-matrix
4	Oxidant	230.0	(506.6)	1144	(1600)	Leaving heater system
5	MHD Gas	330.0	(726.9)	1294	(1870)	Entering heater system
6	MHD Gas	330.7	(728.5)	1289	(1861)	Entering top-of-matrix
7	MHD Gas	330.7	(728.5)	887	(1137)	Leaving bottom-of-matrix
8	MHD Gas	334.4	(736.6)	883	(1130)	Leaving heater system

FIGURE 1. PROCESS DIAGRAM FOR FIXED BED REGENERATIVE  
HEATER SYSTEM

the heater system and the MHD gas flow rate into the heater system were as specified. Flow rates and temperatures indicated at intermediate points in the heater system in Figure 1 account for heat losses and for mass losses due to valve leakage and pressurization/depressurization of the heater system, based on the conceptual design configuration. A description of the heater system configuration, the design approach, and the heater system performance is given in the following sections.

### 2.2.1 Heater System Configuration

The configuration of an individual heater is shown in Figure 2 and the heater system configuration is shown in Figure 3. System parameters are summarized in Tables I and II. Each heater vessel contains a matrix of refractory checkers. The matrix diameter is 7.9 m (26 ft.) and the matrix height is 8.5 m (28 ft.). The matrix is supported by metal girders and checker shoes as in conventional blast furnace stove construction practice. The checkers are high efficiency checkers made of low cost commercial fireclay. One type of checker is shown in Figure 4. Various other checker types could be used without significantly changing the conceptual design and cost estimate. Two internal insulation layers are used, an inner layer of extra strength fireclay castable for erosion resistance, and a moderate temperature insulating castable.

The heater system consists of four individual heaters and the associated ducts and manifolds, as shown in Figure 3. Due to the requirement for large-diameter MHD gas manifolds and sequencing valves, central collectors are provided to distribute the flow from the main gas inlet duct to the individual heaters and from the individual heaters to the main gas outlet duct. These collectors consist of the upper and lower portions of an insulated circular vessel. Two ducts and two valves are provided for the gas inlet and outlet to each heater in order to limit the valve sizes to the values shown in Table II. Single ducts and valves are provided for each vessel for the oxidant inlet and outlet.

The MHD gas manifolds and ducts and the oxidant outlet ducts are internally insulated with the same materials as the heater vessels. The oxidant inlet ducts and manifolds have no internal insulation. All vessels, ducts, and mani-

Technical drawing of a spherical vessel with a vertical cylindrical skirt, showing top, side, and cross-sectional views with dimensions and material specifications.

**Top View:** Shows a circular cross-section with a central circular feature and two rectangular protrusions. Dimensions include a diameter of 6'-4" O.D.

**Side View:** Shows the vessel's profile with a spherical upper section and a cylindrical lower section. Dimensions include a diameter of 26'-8" DIA. and a skirt diameter of 6'-4" O.D.

**Cross-sectional View (Left):** Shows the internal structure with labels for "EXTERIOR INSULATION ON ENTIRE VESSEL SURFACE (TYPE: CALCIUM SILICATE 1/2 IN.)", "GIRDERS", "STIFFENERS", and "LIGHTWEIGHT CASTABLE". Dimensions include a height of 10' and a skirt diameter of 6'-4" O.D.

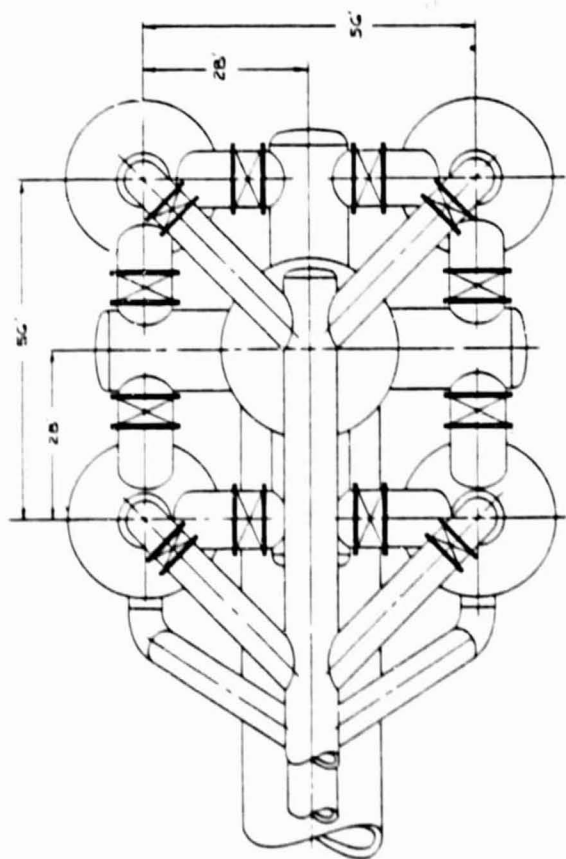
**Cross-sectional View (Right):** Shows the internal structure with labels for "GIRDERS", "STIFFENERS", and "LIGHTWEIGHT CASTABLE". Dimensions include a height of 10' and a skirt diameter of 6'-4" O.D.

**Dimensions:**

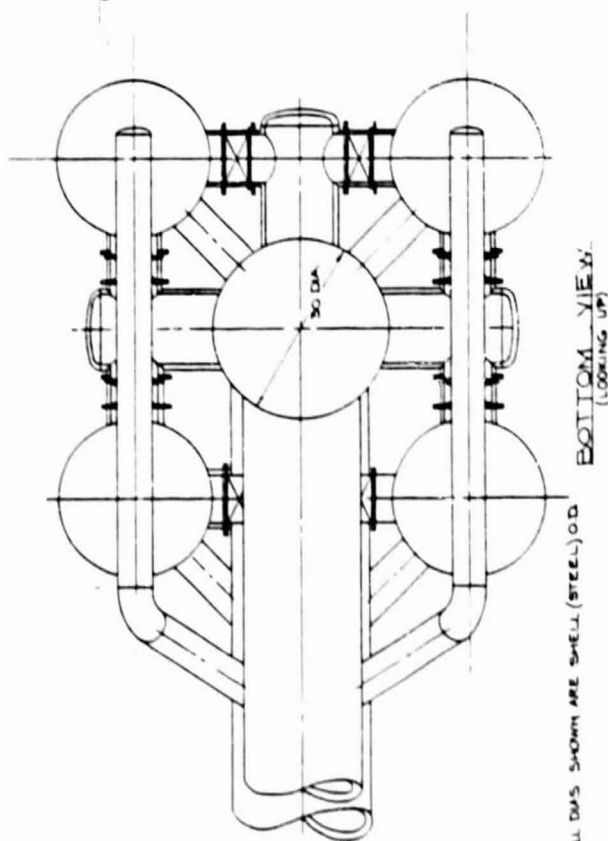
- 6'-4" O.D.
- 26'-8" DIA.
- 6'-4" O.D.
- 10'
- 6'-4" O.D.
- 25'-3" MATRIX HT.
- 7'-11" O.D.
- 4'-0" O.D.

10

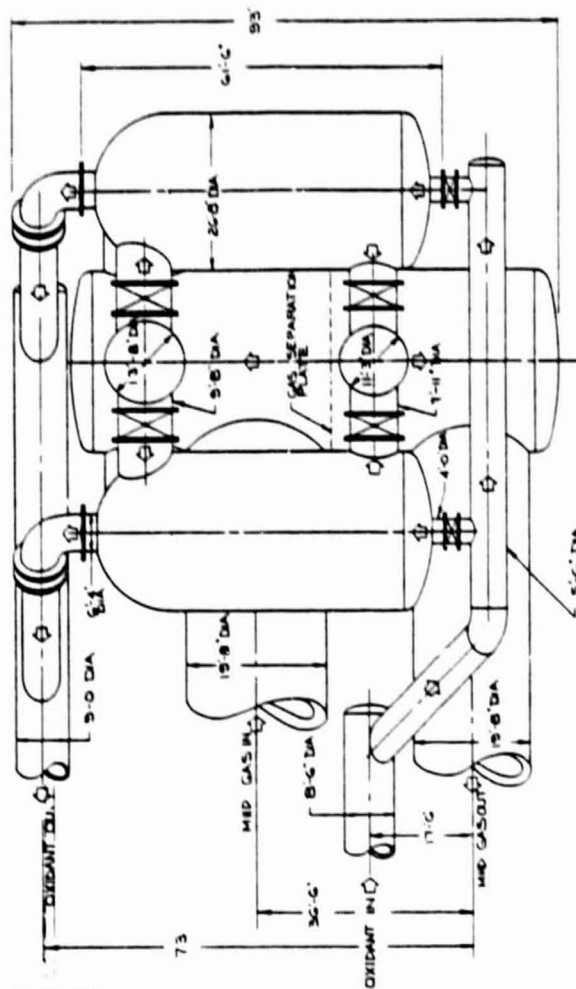




PLAN VIEW



BOTTOM VIEW  
(LOOKING UP)



ELEVATION VIEW

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FIGURE 3. HEATER SYSTEM  
CONFIGURATION

ALL DIMS SHOWN ARE SHELL (STEEL) O.D.

TABLE I - FIXED BED REGENERATIVE HEATER SYSTEM PARAMETERS

CONFIGURATION AND DESIGN PARAMETERS	
Number of Heaters:	4
Matrix Diameter:	7.9 m (26 ft.)
Matrix Height:	8.5 m (28 ft.)
Matrix Material:	Harbison Walker Bison
Matrix Hole Dimension:	33.7 mm (1.328 in.)
Matrix Hole Pattern:	Square
Matrix Web Dimension:	21.3 mm (0.839 in.)
Time on MHD Gas Flow:	1280 sec.
Time on Oxidant Flow:	760 sec.
Time for Switching:	360 sec.
Heater Cycle Time:	2400 sec.
Thermal Stress Limit:	8.6 MPa (1250 psi)
MHD Gas Velocity: Top of Matrix)	27.4 m/sec (90 ft/sec)
SYSTEM PERFORMANCE PARAMETERS	
MHD Gas Pressure Loss:	3.6 kPa (0.53 psi)
Oxidant Pressure Loss:	11.7 kPa (1.7 psi)
System Heat Loss:	4.8% of Heat Duty
Estimated Oxidant Mass Loss to MHD Gas:	4.5 kg/sec (10.0 lbm/sec)
Estimated Carryover of MHD Gas to Oxidant:	0.4 kg/sec (0.9 lbm/sec)

TABLE II - FIXED BED REGENERATIVE HEATER SYSTEM DUCTING AND VALVE CONFIGURATIONS

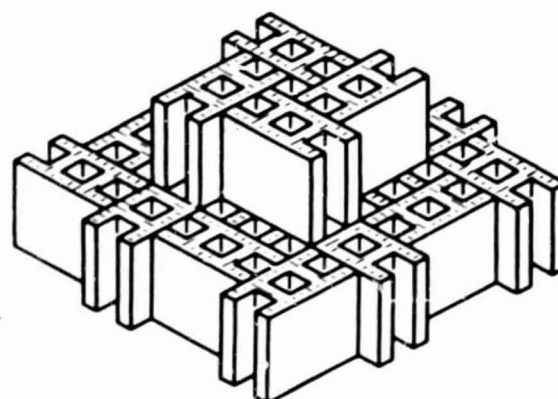
Item	Flow Diameter m (In.)	No. of Valves*	Insulation Thickness		
			Layer 1 <sup>1</sup> mm (In.)	Layer 2 <sup>2</sup> mm (In.)	External <sup>3</sup> mm (In.)
Main MHD Gas Inlet Duct	5.68 (223.5)	-	63.5 (2.5)	88.9 (3.5)	12.7 (0.5)
Central Collector - MHD Gas In	8.78 (345.5)	-	63.5 (2.5)	88.9 (3.5)	
MHD Gas Inlet Manifolds - from Central Collector	3.85 (151.5)	-	63.5 (2.5)	88.9 (3.5)	
MHD Gas Inlet Ducts - to Heater Vessels	2.63 (103.5)	8	63.5 (2.5)	88.9 (3.5)	
Main MHD Gas Outlet Duct	5.79 (228.0)	-	63.5 (2.5)	31.8 (1.25)	
Central Collector - MHD Gas Out	8.89 (350.0)	-	63.5 (2.5)	31.8 (1.25)	
MHD Gas Outlet Manifolds - to Central Collector	3.23 (127.0)	-	63.5 (2.5)	31.8 (1.25)	
MHD Gas Outlet Ducts - from Heater Vessels	2.21 (87.0)	8	63.5 (2.5)	31.8 (1.25)	
Main Oxidant Inlet Duct	2.57 (101.25)	-	-	-	
Oxidant Inlet Manifolds	1.66 (65.25)	-	-	-	
Oxidant Inlet Ducts - to Heater Vessels	1.21 (47.5)	4	-	-	
Main Oxidant Outlet Duct	2.45 (97.5)	-	63.5 (2.5)	69.8 (2.75)	
Oxidant Outlet Ducts - from Heater Vessels	1.65 (65.0)	4	63.5 (2.5)	69.8 (2.75)	

\* Valve flow diameters and internal insulation thicknesses same as for corresponding ducts.

<sup>1</sup> High Strength Fireclay Castable (KS-4)

<sup>2</sup> Insulating Castable (C-20)

<sup>3</sup> Calcium Silicate



KENNEDY

- a. INSTALLATION - SHOWN FOR STANDARD  
CHECKER (FROM REF. 5)

PARAMETER	NO. 1	
	STD.	HIGH EFF.
HEATING SURFACES = A (FT <sup>2</sup> /FT <sup>3</sup> )	8.6	12.06
WEIGHT PER CUBIC = W (LB/FT <sup>3</sup> )	86.22	86.15
FREE CHECKERWK AREA TOTAL CHECKERWK AREA = R	0.3636	0.3681
FLUE SIZE (IN.)	2 in. SQ.	1-21/64 SQ.
MINIMUM WALL THICKNESS BETWEEN FLUES (IN.)	1.250	0.839
HYDRAULIC DIAMETER = D (FT)	0.171	0.115

- b. DIMENSIONS OF CHECKER -  
HIGH EFFICIENCY VERSION  
USED IN CONCEPTUAL DESIGN  
(FROM REF. 6)

FIGURE 4. CHECKER INSTALLATION PATTERN AND  
DIMENSIONS

folds are covered with external insulation. The sizes and insulation thicknesses of the various ducts and manifolds are summarized in Table II.

The heater system configuration offers both compactness and flexibility. The MHD gas central collectors minimize the length of large diameter ducts. The symmetry of the vessels and collector connections will promote uniformity of flow to the individual heaters. Also, because of symmetry and compactness, thermal expansion is readily accommodated. Expansion joints on the ducts will experience smaller movements than if the vessels were aligned in a single row. The MHD gas and oxidant inlet and outlet lines can be arranged in virtually any directions. Therefore, the heater system can be connected to adjacent MHD system components arranged in a variety of possible positions and is thus not limited by layout considerations.

In the individual heater configuration, it should be noted that the vessel plenums are quite compact, i.e., special transition sections on the heater vessels are not required in order to make the gas and oxidant duct connections. For higher temperature applications with thick insulation layers, the presented plenum-to-duct intersection would result in a complex refractory installation requirement. In this instance, however, the use of moderate thickness castable and metallic anchors does not require extensive and expensive molds and installation procedures. A secondary advantage of the compact vessel plenums is a reduction of pressurization/depressurization volume. Flow maldistribution within a single heater can be minimized by appropriate design provision during final design. The small pressure losses in the heaters and ducting and the small length/diameter ratio of the heater matrix are factors which must be considered in addressing this question. The use of two MHD gas inlet ducts will promote uniform gas flow.

The heater concept has two MHD gas inlet and outlet ducts per vessel. However, single ducts can readily be incorporated into the design. The main ducts would be rotated by 45° and the secondary "tee" ducts would be eliminated in such an arrangement. A single large valve may be less expensive and have less leakage, but the availability of such large valves is uncertain. The primary limitations in production of large diameter valves are due to machining the valve seats and shipping of the valves.

The system would be field fabricated because of the size of the primary heater system components. The techniques and procedures are well established from experience with blast furnace stoves or other established industrial applications. All aspects of the heater design and installation are achievable with currently available technology. It is felt that lifetimes on the order of 15-20 years for the refractory checkers and vessel and duct linings and 10-15 years for the sequencing valves should be achievable under the conditions of this application.

Details of major heater system components and operation and performance of the heater system are discussed in the following sections.

#### 2.2.2 Design Approach

A description of the design considerations used to develop the conceptual design for the major heater system components is given in the following paragraphs.

##### Sizing Methods

The heater system was sized by using the Fluidyne regenerative heater system size/cost computer program. This program permits rapid and effective sizing in a manner that allows full consideration of the various design considerations and design constraints. This program has been used extensively for regenerative heater design and design studies for both the DOE and commercial organizations for MHD and conventional applications. Results from this program have been verified by comparison to size predictions made by other methods and by other organizations.

Using the size/cost program, the unique matrix dimensions are determined by the thermal performance requirements and design constraints (fluid pressure loss, allowable thermal stress, ratio of vessels on gas to vessels on oxidant, and allowable temperature droop) at a given design condition and for given matrix geometry and material specifications. Additional design considerations such as bed diameter, bed height, creep limits, solid temperature limits, erosion, and flotation (i.e., buoyancy) restrictions are accommodated in an interactive manner with user interaction. A proprietary algorithm is used based on a longstanding

Fluidyne technique for obtaining regenerator sizes using approximate algebraic sizing equations in conjunction with a rapidly converging finite difference size confirmation routine.

It is possible to derive simplified approximate algebraic equations for the required thermal conductance and for thermal stress during cold blow, as well as a droop/cycle-time equation from the regenerator differential equations. These simplified equations plus the hot and cold fluid pressure loss equations and a semi-empirical regenerator thermal conductance correction equation are sufficient to describe the regenerator.

It is assumed that for the rough surfaces of the cored brick flow passages, the friction factor  $f$  and the convective heat transfer coefficient  $j$  can be adequately expressed as power functions of the Reynolds number  $Re$ ; i.e.,:

a.  $f = f_0 Re^n$  (friction factor)

b.  $j = j_0 Re^m$  (Colburn modulus of heat transfer)

It is then possible to write the three constraining algebraic equations in terms of three unknown geometric parameters defining the matrix volume. Bed length, total system hot fluid flow area, and total system cold fluid flow area are used in the computer program as a matter of convenience. These total system flow areas are the time averaged sums of the number of heaters on hot or cold fluid multiplied by the flow area per heater. The three equations containing three unknowns can be combined algebraically to yield a four term polynomial of one unknown variable. The polynomial is unique for each possible set of three design constraints. Second order effects such as heat loss, gas and particulate radiation heat transfer, entrance and exit pressure losses, and flow acceleration are included in the performance equations as secondary terms. These terms are corrected and improved with each calculation iteration. The polynomial can be explicitly solved for the case when hot fluid pressure loss is the limiting parameter for fixed ratio of hot to cold vessels. In other cases, the first positive root of the polynomial is the physically real solution and it is found using a standard numerical analysis algorithm. For this application, the MHD gas pressure drop and the matrix web thermal stress were the limiting parameters in determining matrix size.



Additional iterative loops are used to establish the cycle time and to correct the calculations if the simplified algebraic equations no longer closely approximate the heater behavior. Establishing matrix volume also fixes matrix mass which in turn establishes the cycle time required to give a specified regenerator droop. Having the mass and droop, the semi-empirical thermal conductance correction equation can be applied as needed. If the deviation is beyond the specified tolerance, the required thermal conductance is corrected, leading to a further iteration through the sizing algorithm. This iteration is always done at least twice to provide assurance that the second order effects are adequately accounted for in the governing equations.

Finally, because the semi-empirical corrector is valid over a finite performance range, the "final" iterative loop uses a finite difference performance prediction algorithm. The loop is repeated until mean delivered oxidant temperature and oxidant droop converge to within a specified tolerance.

Once matrix sizing is completed, a complete thermal/hydraulic description of the system is generated. The gross volume is divided into a discrete number of vessels and dimensions are computed. The total system matrix mass is adjusted to allow for switching from gas to oxidant.

The basic size and performance information from the computer program were used to generate the heater system layout. Costing algorithms in the computer program are also used to predict the cost of the entire heater system, but the cost estimate for the system presented herein was manually generated as described in Section 2.3.

The heater design basis was also confirmed by using one of several Fluidyne performance simulation computer programs. The version used provided temperature response for a heater system of identical vessels. The selected program also provided information on matrix cyclic thermal stresses and the matrix/wall interaction. A program designed to simulate a highly interactive system (including flow redistribution, duct capacitance, etc.) is available, but its usage was beyond the scope of the current effort.



### Number of Heaters

Regenerative heaters up to 10.4 m (34 ft.) in diameter are state-of-the-art in high temperature industrial applications. The primary limitation is due to vessel dome construction and pressure containment. For this application the dome construction is simplified because the 1294 K (1870 F) hot gas inlet temperature is low enough that castable refractory insulation with metallic anchoring can be used. The oxidant pressure level of 6 atm is also modest. Therefore, the number of heaters was not constrained by vessel diameter limitations.

The number of heaters was, therefore, selected by layout and valve size considerations. Two valves were used for each vessel for both the MHD gas inlet and outlet. The 2.7 m (9 ft.) diameter inlet valve for the MHD gas is near the upper limit for manufacturing without development of a very large milling machine to produce the gate valve seats. Given four heaters with paired hot gas valves, the system layout shown in Figure 3 was developed.

Extensive optimization of the number of heaters was beyond the scope of the conceptual design, but it is believed that any effect on total estimated system cost would be small.

The ratio of time averaged number of heaters "on gas" to those "on oxidant" was determined by the design requirements. There are approximately 2.1 heaters "on gas," 1.3 heaters "on air," and 0.6 heaters "on pressurization/depressurization" on a time averaged basis over a full heater cycle.

### Matrix

The matrix material is a commercial fireclay product (Harbison-Walker "Bison"). This is a low cost material rated for moderate temperature applications which offers a particularly good compromise between base material cost and thermophysical properties. This is illustrated in Table III, in which material parameters for a number of potential matrix materials (both production and experimental) are compared.

TABLE III - CANDIDATE FIXED BED REGENERATIVE HEATER SYSTEM MATRIX MATERIAL  
THERMAL STRESS AND ENERGY STORAGE PARAMETERS

Material	Estimated Max. Service Temp.*		Thermal Stress Parameter		Energy/Cost Parameter		Energy/Volume Parameter	
	K	(F)	$\frac{m}{W}$	$\left(\frac{hr-ft}{BTU}\right)$	$\frac{kJ}{\$-K}$	$\left(\frac{BTU}{\$-F}\right)$	$\frac{MJ}{m^3K}$	$\left(\frac{BTU}{ft^3-F}\right)$
Norton AH 199B	1980	(3100)	.0149	(.0143)	.64	(.34)	4.5	(67)
HW Mullite	1645	(2500)	.0152	(.0146)	1.20	(.63)	2.7	(40)
HW Silica, Vega	1810	(2800)	.0029	(.0028)	2.37	(1.25)	2.3	(34)
HW Ufala	1590	(2400)	.0095	(.0091)	1.61	(.85)	2.6	(39)
HD Fireclay	1255	(1800)	.0060	(.0058)	3.68	(1.94)	2.1	(32)
Rebonded X-317	-	-	.0152	(.0146)	.27	(.14)	3.2	(47)
Green Valentine XX	1505	(2250)	.0156	(.0150)	4.35	(2.29)	2.5	(37)
HW XD Mullite	1730	(2650)	.0101	(.0097)	.95	(.50)	2.6	(38)
HW SD Fireclay	1395	(2050)	.0158	(.0152)	2.01	(1.06)	2.3	(34)
Carborundum Monofrax A	2115	(3350)	.0061	(.0059)	.09	(.05)	3.6	(53)
Carborundum Monofrax K3	2060	(3250)	.0111	(.0107)	.11	(.06)	5.7	(85)
HW Ruby	2005	(3150)	.0212	(.0204)	.65	(.34)	3.4	(50)
HW Bison	1480	(2200)	.0123	(.0118)	3.42	(1.80)	2.7	(40)

\* For matrix application - no slag attack -  
load assumed to be 0.2 MPa (30 psi)

$$1 \quad \frac{\alpha E}{\sigma_{MOR} (1-\nu)k}$$

2 c/unit cost

3  $\rho c$

Three parameters are shown in Table III:

$$\text{thermal stress parameter} = \frac{\alpha E}{\sigma_{\text{MOR}} (1-\nu)k}$$

$$\text{energy/cost parameter} = \frac{c}{\text{UC}}$$

$$\text{energy/volume parameter} = \rho c$$

where  $\alpha$  = coefficient of thermal expansion

$E$  = modulus of elasticity

$\sigma_{\text{MOR}}$  = modulus of rupture

$\nu$  = Poisson's ratio

$k$  = thermal conductivity

$c$  = specific heat

$\rho$  = density

UC = unit cost, \$/mass

A low thermal stress parameter is desirable since thermal stress tends to be design limiting, i.e., the allowable thermal stress limits the maximum cold fluid heat transfer coefficient. The energy/cost parameter should be high since it is an indication of the amount of energy that can be stored per unit cost of matrix material. The energy/volume parameter should be high since it is an indication of the amount of energy that can be stored per unit volume which in turn affects containment vessel costs. Other factors which must be considered in selection of a matrix material include corrosion/erosion resistance, crushing strength, service temperature limits, and any unique properties of particular materials.

Based on Table III, a likely candidate is high duty fireclay. However, this material has a maximum service temperature of only about 1256 K (1800 F). Allowing some margin of safety, high duty fireclay could be used in the part of the matrix with maximum temperatures less than 1140 K (1600 F). This would be recommended for consideration in a more detailed design study. Two other likely candidates from Table III are high silica, "Vega," and semi-silica "Valentine XX." These materials have unique properties that result from the silica content. One of these properties is the coefficient of thermal expansion which is unusually high over a specific temperature range. As a consequence, special design and operating provisions would be required during startup and shutdown if these materials were used. Of the remaining materials, Bison was selected as a good commercially available material that meets the design criteria. This material has a sufficient service temperature rating and crushing strength and is also expected to have sufficient corrosion and erosion resistance in this application. Other materials not shown in Table III would also be suitable, and should be considered in the final design phase.

The heater matrix refractory shape is a high efficiency checker variously known as a Kennedy, Bailey, or Andco checker. This is a simple, "compact" checker commercially available in production quantities. This checker has square holes nominally 33.7 mm (1.328 in.) on a side and 21.3 mm (0.839 in.) ligaments or webs. The checker arrangement for a regenerative heater application is illustrated in Figure 4. A comparable checker can be obtained from several manufacturers.

Several other checker shapes would also be suitable for use in the heater system. Modern blast furnace stoves typically use interlocking checkers, such as the M and P checker recommended by Andco Technical Services, Inc. Such checkers are available with circular holes of 36 mm (1.417 in) or 40 mm (1.575 in) diameter. The selection of a different high efficiency checker shape will not significantly alter the heater system dimensions or the performance as determined for the conceptual design presented herein.

The selected matrix represents a conventional design. Furthermore, both the material and the hole pattern are compatible with the particulate bearing hot gas stream. Departure from the proposed matrix to a more compact design, such

as one with 19 mm (3/4 in.) diameter holes and 9.5 mm (3/8 in.) webs is conceivable, but could result in fabrication risks and fouling risks. Development work could then be required to reduce these risks.

#### Allowable Thermal Stress

Tensile thermal stresses are developed due to the temperature gradient induced in the matrix material when the cold oxidant flows through the matrix. A maximum allowable thermal stress level, based on a theoretical elastic model, was imposed to insure that cracking of the matrix bricks will not occur. The nominal allowable thermal stress that was used was 8.6 MPa (1250 psi), which is one-half of the modulus of rupture (MOR) of the matrix material at room temperature. This value is expected to be valid over the temperature range encountered in this application. The design was thermal stress limited; this means that both the cold side mass velocity and the amount of pressure loss that could be used to promote heat transfer were limited by the allowable thermal stress. Additional work will have to be done in the preliminary or final design stage to provide assurance of acceptable flow distribution within the heater matrix because of the relatively low cold fluid pressure loss (11.7 kPa, 1.7 psi) as well as the small length/diameter ratio of the matrix.

#### Pressurization/Depressurization

In a regenerative heater system a portion of the total cycle time must be used to provide time for valve movements and to switch from one fluid to the other at a suitable pressurization/depressurization rate. Fired applications such as blast furnace stoves provide flexibility because the firing rate and duration can be independently controlled. In a MHD plant all of the hot gas must flow through the system at a continuous rate. Therefore, additional matrix is needed in direct proportion to the fractional time that is allocated for vessel switching. An equivalent of 0.6 heaters or 15% of total matrix mass is attributable to switching.

The allocation of switching time is somewhat arbitrary at the conceptual level of analysis. More detailed analysis and design work could lead to a reduction of this "unproductive" heater volume. It is unlikely, however, that the

allowance could be reduced by any more than a factor or two. The major factors involved are:

1. Valve cycling frequency;
2. Pressurization/depressurization valve type and size;
3. Allowable system temperature, pressure, and flow variations and
4. Matrix mass per unit of heat transferred.

#### Thermal Insulation

The maximum service temperature is moderate so that the vessel and duct insulation scheme is straightforward. Inexpensive, highly thermal resistive castable refractory attached by metallic anchors can be used. The design parameter for insulation sizing was a nominal surface heat flux of  $1340 \text{ W/m}^2$  ( $425 \text{ Btu/hr ft}^2$ ), or an outer skin temperature of approximately  $390 \text{ K}$  ( $250 \text{ F}$ ). A nominal steel vessel temperature of  $480\text{--}530 \text{ K}$  ( $400\text{--}500 \text{ F}$ ) was desired to prevent corrosion due to  $\text{NO}_x$  or  $\text{SO}_x$  species. External insulation was specified in order to maintain the necessary steel vessel temperature. A liner using a high strength fireclay castable was selected to provide erosion resistance. A thickness of  $63.5 \text{ mm}$  ( $2.5 \text{ in.}$ ) was selected as the minimum for simple installation procedures. Where appropriate, a second insulating layer of the equivalent of Harbison Walker Castable 20 was used to reduce total insulation costs.

Castable insulation is generally not used in blast furnace stoves. However, castables have found extensive application in the chemical process industries. Castable refractory insulation will require provision for thermal expansion to avoid cracking. In industrial applications such as secondary ammonia reformers (Ref. 25) gaps are typically produced by casting or gunning the liner materials in sections and by covering the metallic anchors with combustible material. Upon initial firing of the structure the material "burns out," and produces gaps when the structure is cold. When heated to operating temperatures, the gaps close to maintain insulation integrity. If the particulate-laden gas only flows through the vessel while it is hot, there will be little, if any, tendency for

ratcheting to occur. Ratcheting in this context results from repetitive cycles where particulate material fills the gaps, restraining thermal movement and causing a progressive increase in gap dimension leading to refractory failure. It is not anticipated that this will occur in this application. However, as a contingency, a brick type structure could be considered in the final design with a corresponding cost penalty. Brick type linings are recommended by blast furnace stove manufacturers.

The types of insulation and the thicknesses of the insulation layers in each section of ducting are indicated in Table II and Appendix D. Only the air inlet manifold and ducts were not internally insulated. If, however, the hot gas outlet temperature were reduced by either increasing the oxidant outlet temperature or by bypassing a fraction of the hot gas stream and thus reducing the flow of MHD gas through the individual heaters, the gas outlet piping and the lower vessel plenum might also require only external insulation. This would result in an insulation cost savings. However, bypassing part of the MHD gas would increase the control needs and costs.

The total estimated heat loss for the heater system is 4.8% of the heat duty. A heat loss vs. system cost tradeoff was not made because of the limited scope of this study. Optimization would have a minor effect on total system cost.

### 2.2.3 Heater System Operation and Performance

The full-load operation and performance of the heater system as configured in the conceptual design is discussed in this section.

Table IV indicates major events for a single heater as a function of time over one complete cycle. Each of the four heaters follows the same sequence of events, but the heater operations are staggered in time by 1/4 of a cycle. The timing diagram, Figure 5, shows the relationship of the operating sequence for the four individual heaters.

Assuming identical heater performance and instantaneous valve movements, the flow per heater vessel as a function of time is as shown in Figure 6. This flow function yields the predicted single heater fluid outlet temperatures



TABLE IV - FIXED BED REGENERATIVE HEATER SYSTEM  
(SINGLE HEATER UNIT)

Event	Starting Time, Sec.	Interval, Sec.
Air valve opening, half to full	0	10
Air valve full open	10	750
Air valve closes	760	20
Depress. valve opens	780	7
Depress. valve full open	787	112
Depress. valve closes	899	7
Gas valve opening, to half	906	22
Gas valve opening, half to full	928	22
Gas valve full open	950	1258
Gas valve closes	2208	44
Press. valve opens	2252	7
Press. valve full open	2259	124
Press. valve closes	2383	7
Air valve opening, to half	2390	10
Air valve opening, half to full	0	10
Cycle Repeats		



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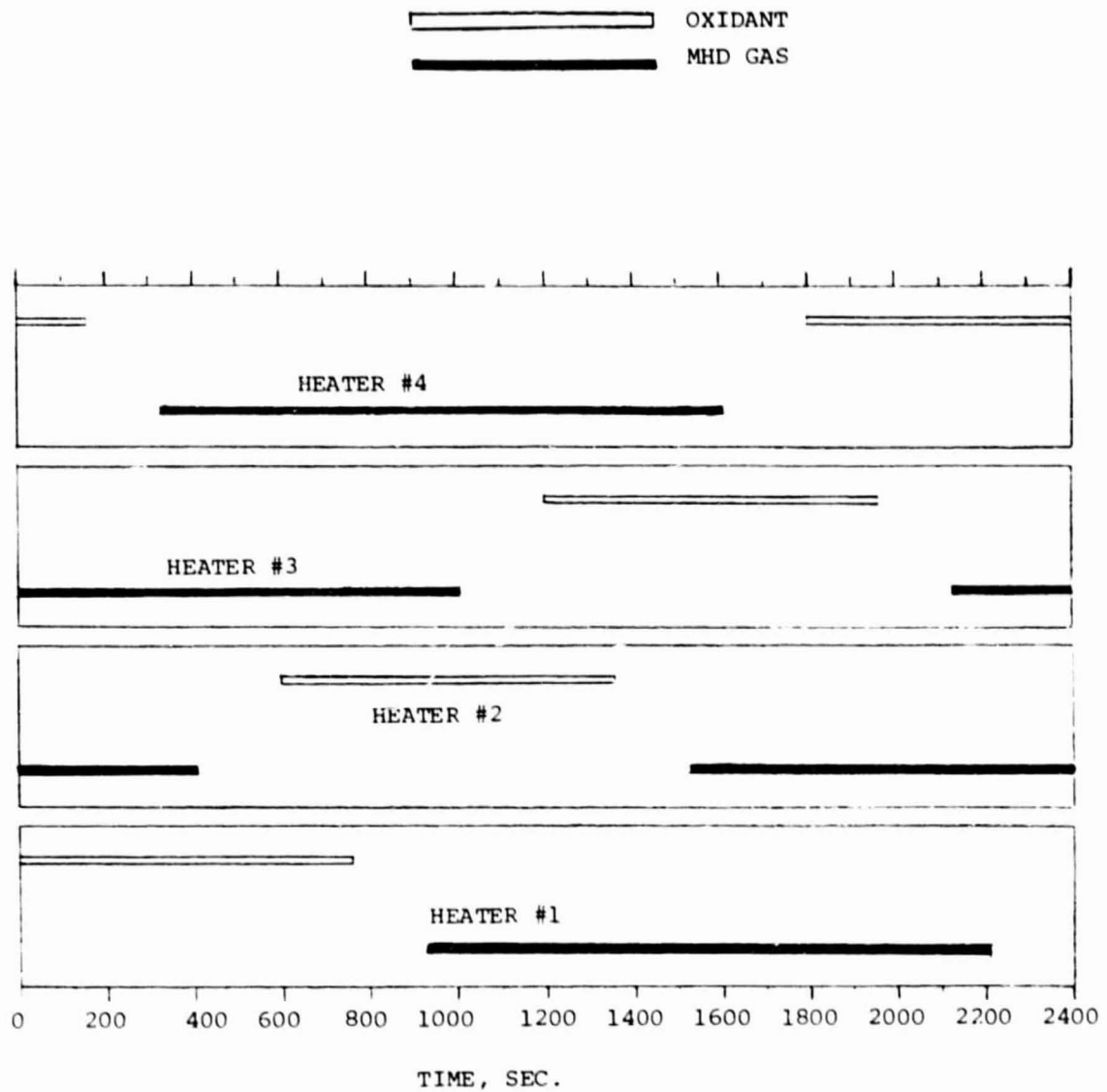


FIGURE 5. TIMING DIAGRAM FOR FLOW OF OXIDANT AND MHD GAS  
THROUGH HEATER SYSTEM

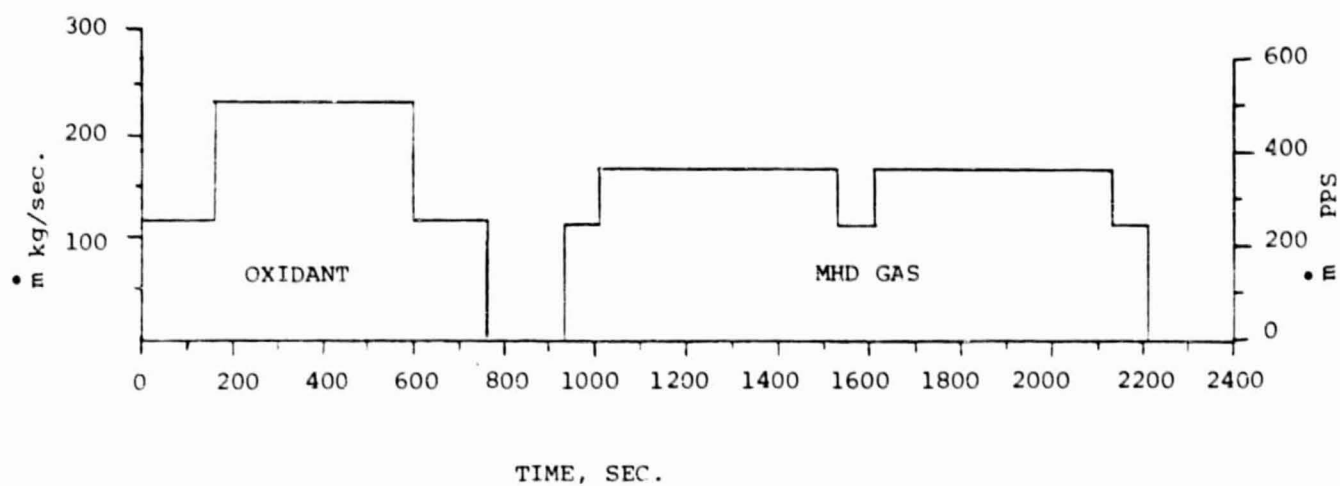


FIGURE 6. IDEALIZED FLOW RATE OF OXIDANT AND MHD GAS THROUGH AN INDIVIDUAL HEATER

over a cycle as shown in Figure 7. Using this data in conjunction with the system timing diagram yields the estimated heater system oxidant and combustion gas outlet temperature functions as shown in Figure 8. Note that these calculations do not include any allowance for control, differences in individual heater conditions, or flow passage capacitance. Additional typical single heater performance data are given in Figures 9 and 10. Figure 9 provides the end-of-phase axial matrix temperature distributions as a function of bed height. Figure 10 provides matrix and liner radial temperature profiles at several axial locations. The effects of heat loss and matrix/liner thermal interaction have been included in these calculations.

### Ripple

Predicted heater system oxidant and MHD gas outlet temperatures are shown in Figure 8. The saw-tooth profile is characteristic of regenerative heaters. The timewise variation in temperature is known as ripple and is caused by the temperature droop of the individual heaters. The oxidant ripple can affect combustor and channel performance, and could, conceivably, feed back into the heater system. The hot gas ripple could thermally cycle downstream components. The temperature ripple is strongly linked to:

1. Number of heaters;
2. Matrix mass required to accommodate switching; and
3. Matrix mass per unit of heat transferred at fixed flows and inlet temperatures.

The latter is, in turn, strongly linked to matrix material properties, checker selection, and required thermal performance.

The oxidant temperature ripple predicted for the presented conceptual design amounts to a total peak to peak variation of 80 K (140 F); i.e., the outlet temperature varies by  $\pm 40$  K (70 F) about the average value of 1144 K (1600 F). A system with a higher delivered oxidant temperature and a smaller ripple could be

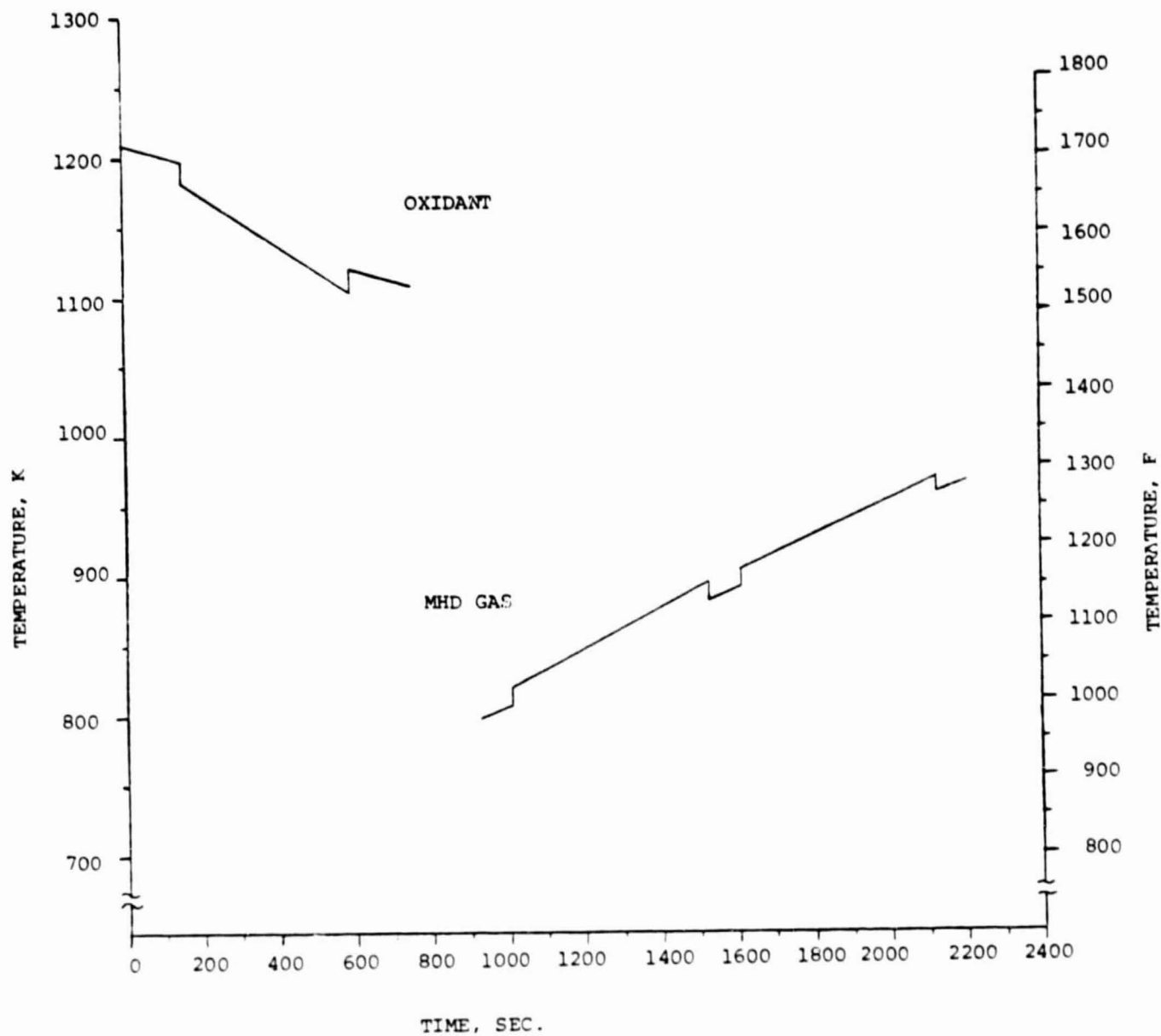


FIGURE 7. FLUID TEMPERATURES LEAVING INDIVIDUAL HEATER MATRIX

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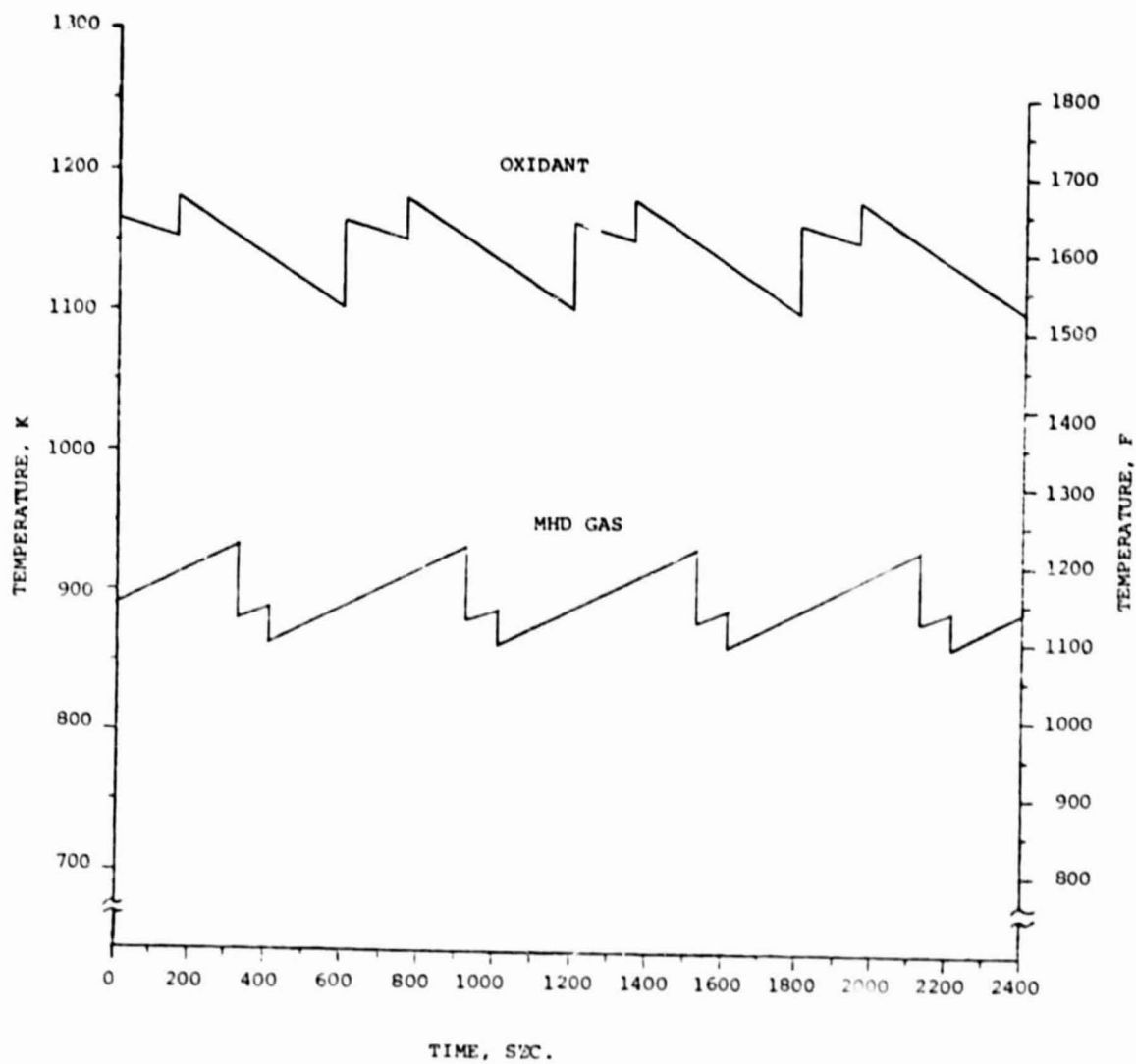


FIGURE 8. FLUID TEMPERATURES LEAVING HEATER SYSTEM

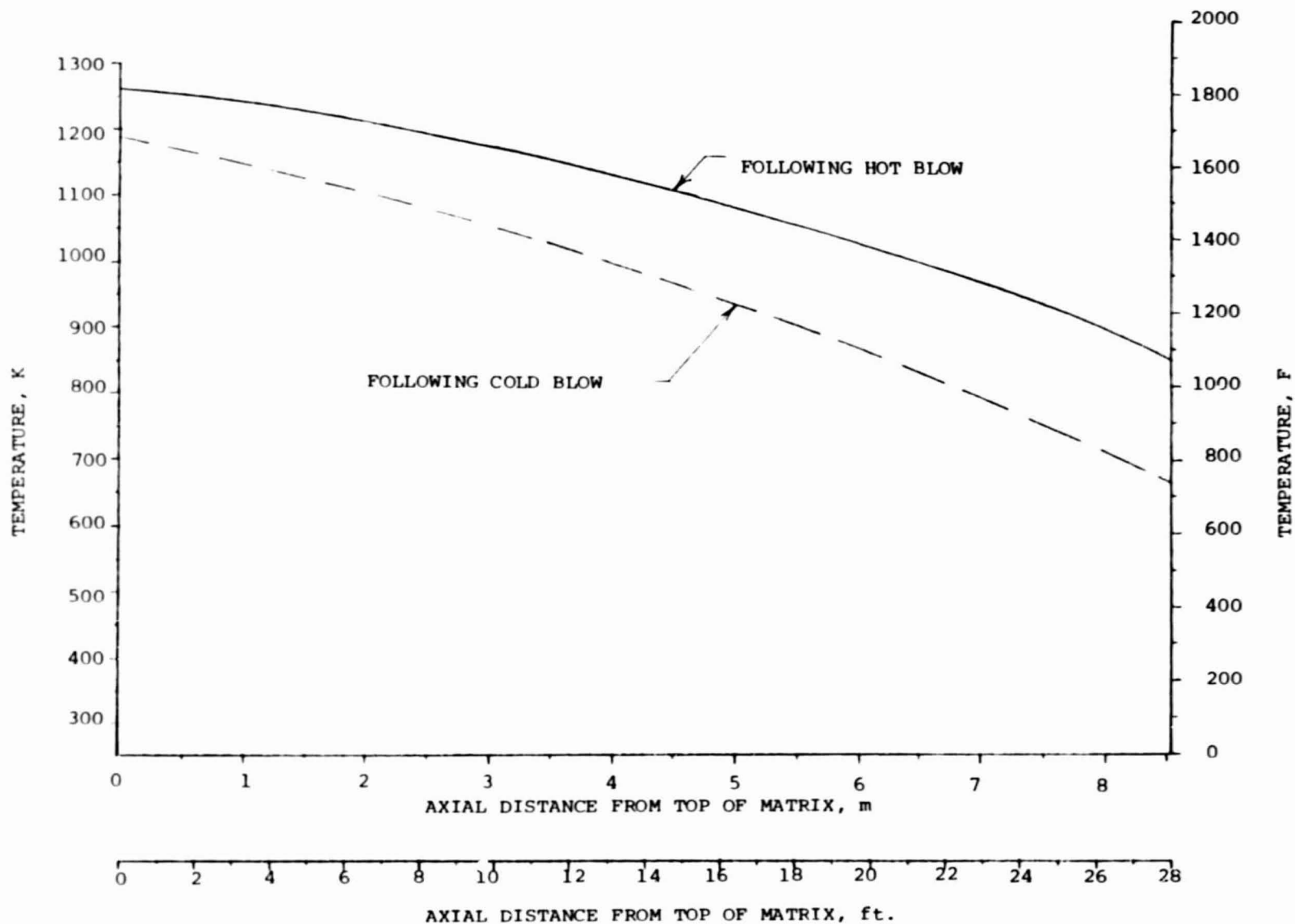


FIGURE 9. INDIVIDUAL HEATER MATRIX AXIAL SOLID TEMPERATURE PROFILES

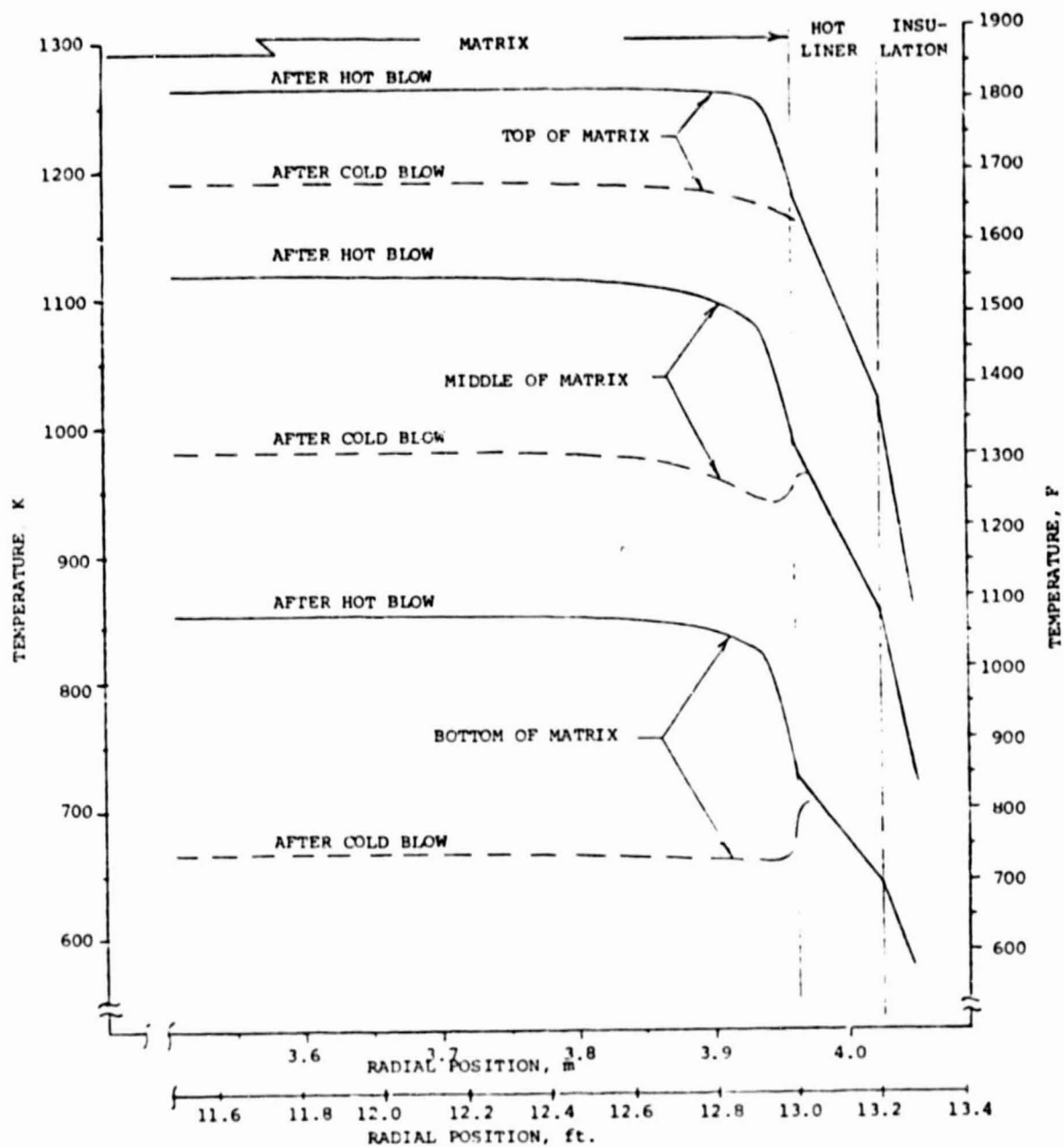


FIGURE 10. INDIVIDUAL HEATER RADIAL TEMPERATURE PROFILES AT THREE AXIAL MATRIX POSITIONS

configured with the same inlet gas temperature, as discussed below. The ripple can also be reduced for the same oxidant temperature level by reducing the cycle time; this would require a larger number of valve cycles in a year and thus would increase valve wear.

#### Heater System for Increased Oxidant Temperature

The presented design has a modest bed height (8.5 m or 28 ft.), and the vessel cost represents a relatively small portion of the heater system cost. Therefore, it appears reasonable to consider a design yielding an oxidant temperature at the heater system outlet as high as 1214 K (1725 F). To this end, Figure 11 was prepared showing relative vessel cost as a function of delivered oxidant temperature. The MHD Gas inlet temperature and the number of heaters were held constant in developing this information. As the oxidant thermal effectiveness increases, i.e., as the temperature increase of the oxidant in the heater system more nearly approaches the difference between the MHD gas inlet temperature and oxidant inlet temperature, the required heat transfer area increases proportionately more than the oxidant temperature. Thus, the matrix mass per unit of heat transferred increases and the decrease in outlet temperature in a given time interval (droop) decreases. One can then choose either to allow the cycle time to increase or to reduce the individual heater droop and thus the heater system ripple. In developing the data in Figure 11, the cycle time was held nearly constant and the ripple was allowed to decrease. For this reason, ripple is also plotted as a function of delivered oxidant temperature.

An increased oxidant temperature will improve MHD plant performance. For example, information from the NASA Lewis Research Center indicated that an increase in oxidant temperature from 1144 K (1600 F) to 1214 K (1725 F) would increase overall MHD plant efficiency by approximately 0.4 of a percentage point. Increased oxidant temperature also offers the possibility of decreasing the temperature ripple with bypass oxidant flow in order to achieve a more nearly constant oxidant temperature if this is desirable.



MHD GAS INLET TEMPERATURE= 1294K (1870F)

NUMBER OF HEATER VESSELS = 4

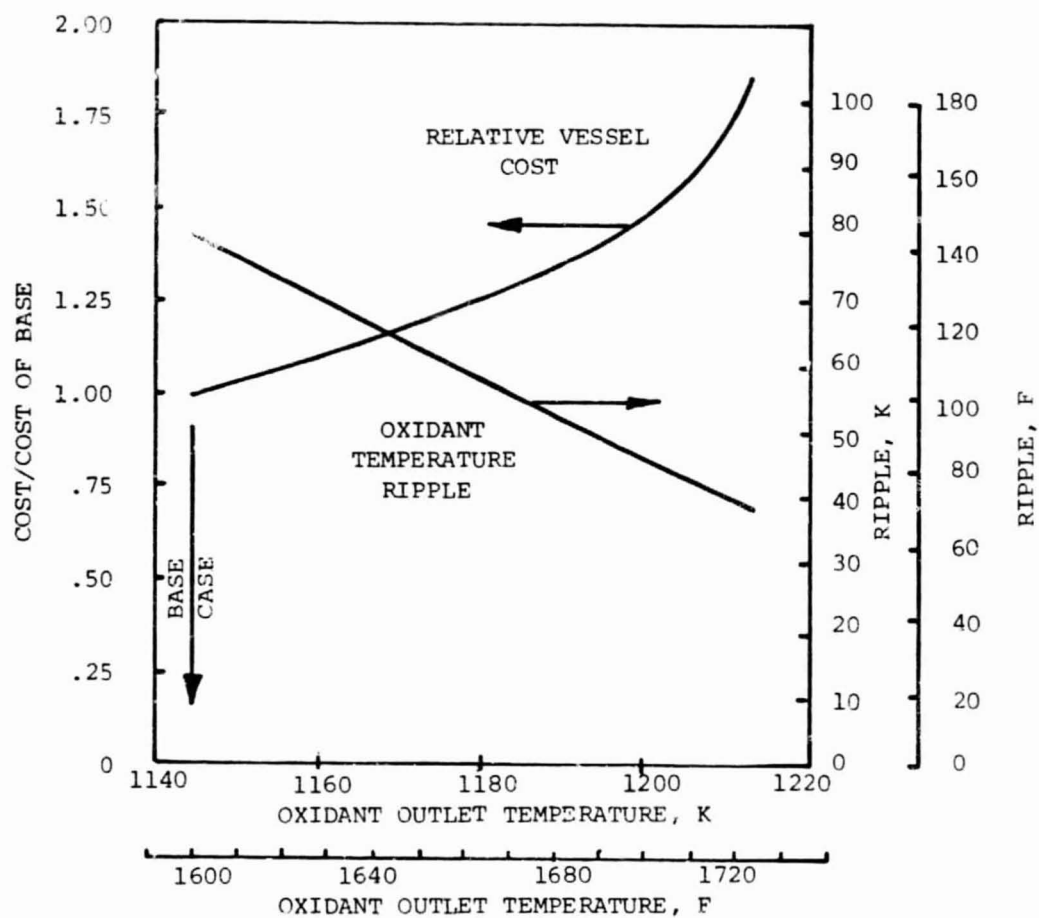


FIGURE 11. RELATIVE VESSEL COST AND OXIDANT TEMPERATURE RIPPLE FOR INCREASED OXIDANT PREHEAT TEMPERATURES

A continuous bypass of a fraction of the MHD gas stream could be beneficial. Although the required matrix mass would increase, the cross-sectional areas of the MHD gas ducts and valves and the maximum bottom-of-the-bed solid temperature (and thus the bed support temperature requirement) would decrease. For example, bypassing 30% of the MHD gas could result in a maximum bottom-of-the-bed solid temperature of 617 K (651 F). Increasing the oxidant temperature as suggested above would also reduce the maximum bed support temperature requirement.

### Control Considerations

Design of the regenerative heater control system and the MHD system controls required by the regenerative heater system requires data that is not available on a conceptual design basis. Allowance was made in the cost estimate for general process instrumentation and controls based on previous work. Hydraulic systems with attendant controls were included in the valve cost estimates.

There will be variation in both outlet streams with respect to temperature, pressure, flow rate, and fluid composition. Of these, temperature is most likely to be significant. The oxidant composition will vary due to carryover of hot gas and particulate matter because of the switching process.

The oxidant and MHD gas temperatures could be controlled by means of bypass of MHD gas and/or oxidant. The flows could be controlled to modulate the heater system outlet temperatures if required by the combustor and/or downstream components. Some degree of protective system control would be required to prevent overpressure or overtemperature in the MHD gas ducts and excessive thermal cycling of the refractory materials in the heater system due to channel performance fluctuations.

### 2.3 Cost Estimate

A cost for the fixed bed heater system described above was estimated. The estimate, which includes cost of materials, fabrication and installation, is \$19,298,000 in 1980 dollars. A summary of the costs by major component is given in Table V.

TABLE V - FIXED BED REGENERATIVE HEATER SYSTEM ESTIMATED COST

COMPONENT DESCRIPTION	COST (\$1,000's)
Heater Vessels (4)	
Steel Shell	1525
Refractory Insulation (installed)	596
Checker Matrix (installed)	2939
Matrix Support (installed)	1552
	<hr/>
Total Heater Vessels	6612
MHD Gas and Oxidant, Ducting (with installed insulation)	2283
Sequencing Valves	6548
Major Expansion Joints	462
Support Structure and Foundations	1639
Controls and Instrumentation	877
Erection (excluding refractory installation)	877
Total HEATER SYSTEM	<del>19298</del>

Several important results can be seen from the cost summary. First, the flow sequencing valves are a major cost component in the heater system, representing 34% of the total cost. If the valves could be reduced in size or number, there would be a substantial savings in total heater cost. Therefore, tradeoffs between allowable velocity in the valves (with erosion and poor flow distribution that results from high velocity) and heater system cost should be considered in future design studies.

Second, the matrix of refractory checkers amounts to only 15% of the total system cost based upon using a single material for the entire matrix; checker material cost alone (not installed) represents only 9% of the system total. Thus, the specific refractory material selected for the heater matrix makes little difference to overall cost. Using the lowest cost material suitable for the bottom portion of the matrix, such as high duty fireclay, will not significantly reduce the heater system cost.

Furthermore, using a heater matrix of increased height to produce a higher outlet temperature of the oxidant, as proposed in Section 2.2.3, will not significantly increase the heater system cost. Based on the results from that section, a heater system delivering oxidant at 1210 K (1720 F) would have a total installed cost of approximately \$24 million.

The basis for the cost estimate is discussed in the following sections, and a detailed cost breakdown is provided in Appendix D.

#### 2.3.1 Basis for Cost Estimate

Costs were estimated using the following general guidelines:

- The costs of all materials, shop fabricated components, and purchased equipment are F.O.B. manufacturer's plant, i.e. ready-to-ship. No shipping costs from manufacturer to site are included.
- Rates for field labor or shop labor are based on \$42 per hour which includes direct wages and indirect charges such as supervision, insurance fringe benefits, workers compensation, support staff, tools

and equipment, contingency and contractor fee or profit. This rate is converted to a basis of dollars per pound or dollars per cubic foot in some instances.

- Engineering design costs are not included.
- Indirect costs and contractor profit or fee have not been specifically added to the costs for purchased components but are included through the application of the labor rates specified above.
- Costs were established directly from the weights, volumes, or capacities of the components listed.
- In the cases of structural steel, instrumentation and controls and field erection and assembly, quantities or costs were estimated as percentages determined from previously installed test facilities and ceramic heaters designed by Fluidyne or from previous studies of ceramic heaters.

### 2.3.2 Steel Components

Material and fabrication cost rates for the types of steel used in the system are given in Table VI.

TABLE VI - ESTIMATED COSTS FOR STEEL

TYPE OF STEEL	Field or Shop		
	Material Cost	Labor Rate	Fabricated Cost
	(\$/lb)	(\$/lb)	(\$/lb)
Carbon Steel	.35	1.25	1.60
Structural Steel	.35	.25	.60

### 2.3.3 Refractory Materials

The cost rates for the types of refractories included in the facility are given in Table VII. Factors were applied to account for rebound (loss of castable material when gunning on to a surface) and for anchors to hold the castable material in place; for manufacturing the checker shape; and for supporting the external insulation.

### 2.3.4 Refractory Installation

Refractory installation costs are based on the following determination of cost per unit volume of installed refractory:

- There are 17.2 nine inch equivalents (equal to the volume of a standard 9" x 4.5" x 2.5" refractory brick) in one cubic foot.
- Labor hours required per nine inch equivalent are
  - .0375 hours/9 in. equivalent (for installation)
  - .0075 hours/9 in. equivalent (for materials handling)
  - .0450 hours/9 in. equivalent

Therefore the basic installation cost rate is:

$$(.0450) (17.2) (42) = 32.50 \text{ \$/ft}^3$$

This installation rate is multiplied by complexity factors, some of which reduce the rate and some of which increase the rate. Typical complexity factors and the resultant rates are given in Table VIII.

### 2.3.5 Sequencing Valves

The costs of all valves were estimated by the following procedure:

- The weight of a single-plate valve of the given bore for dirt-bearing media service was determined from blast furnace valve vendor literature.

TABLE VII - ESTIMATED COSTS FOR REFRACTORY MATERIALS

LOCATION	Refractory Type	Material Cost (\$/lb)	Adjusted Material Cost, Incl. Rebound Checker or Support Factors (\$/lb)
Heater			
Hot Liner	Castable, KS-4	.214	.28
Inner Liner	Castable, C-20	.46	.60
Bottom Fill	Lightweight Castable	.46	.46
Matrix (Holed)	Checker, HW Bison	.237	.31
Piping	Castable, C-20	.46	.60
	Castable, KS-4	.214	.28
External Insulation	Calcium Silicate	1.00	1.05

TABLE VIII - ESTIMATED INSTALLATION COSTS FOR REFRACTORY MATERIALS

Refractory Category	Complexity Factor (Multiplier)	Installation Cost Rate (\$/ft <sup>3</sup> )
External Insulation	0.7	22.75
Castable Material	0.8	26.00
Large Horizontal Diameters	1.0	32.50
Heater Matrix	1.0	32.50
Upper Domes in Vessels	2.0	65.00
Heater Bottom Fill	0.75	24.38

- A basic valve cost of \$6.00 per pound was applied. This was derived from known costs of similar valves furnished by major valve manufacturers.
- 10% was added to the basic cost of each valve for a hydraulic operator.
- If the valve was internally insulated, 20% was added to the basic cost.

#### 2.3.6 Expansion Joints

It was assumed that each heater duct will require an expansion joint. Recent quotations from manufacturers on similar size expansion joints were used to establish the expansion joint cost.

#### 2.3.7 Additional Costs

The cost of controls and instrumentation was estimated at 5% of the total cost of all materials, shop-fabricated components, purchased equipment and refractory installation.

An identical amount was added for erection and assembly of the system. Based on the overall system cost and weight, this 5% allowance translates into an erection and assembly cost of approximately 9 cents per pound. This rate is somewhat low compared to rates we have used in other work but seems justified in this case since most of the weight is highly concentrated in the heater assembly package. It should be noted that the cost of erection and assembly does not include refractory installation which was treated separately and is discussed in paragraph 2.3.4.



### 3.0 CERAMIC RECUPERATIVE HEATER SYSTEM

The major design considerations, conceptual design and cost estimate for a tubular ceramic recuperative heater for the MHD intermediate temperature oxidant heater application are discussed below. The presented conceptual design does not represent an optimized heater system, since the level of effort required for optimization was beyond the scope of this study. In contrast to the fixed bed regenerator conceptual design which would utilize materials, components, and fabrication techniques which represent standard industrial practice, the ceramic recuperator would require considerable development effort as well as expanded manufacturing capabilities in order to produce the required ceramic components.

#### 3.1 Design Considerations

##### 3.1.1 Design Considerations for MHD Application

The major design factors involved in adapting the ceramic tube and shell recuperator to this application are (1) the large pressure difference between MHD gas and oxidant, (2) the large flow rate to be handled compared to flow rates in current applications, and (3) the MHD gas particulate loading. A ceramic recuperator would require thin walled structures (tubes and headers) manufactured from brittle (ceramic) materials. As opposed to standard uses of ceramic materials (bricks, castables, etc.), such structures present several challenging design problems, including accomodation of thermal expansion and development of fabrication techniques for metal/ceramic interfaces and ceramic tube and header assemblies.

The major design factors related to the pressure difference are the ability of ceramic materials to withstand the applied stresses and the possibility of leakage through the many joints. The pressure containment requirement limits the size of ceramic tubes and headers; the large overall heater size thus requires a number of modules containing relatively small ceramic components. All joints involving ceramic components are of great concern due to the potential for leaks. If a leak-free assembly can be constructed, thermal expansion and mechanical and thermal stresses during operation could cause leaks to develop.

These design factors along with the variability of mechanical properties of ceramic materials and the resulting uncertainties in design procedures, are

identified in Refs. 4, 26 and 27 as the major limitations in applying ceramic recuperators to the MHD oxidant heating requirement.

The particulate loading in the MHD gas stream also restricts the design. Small flow passages would be subject to fouling, and slip-type joints or gaps in ceramic components could become fouled with dust. The particles are expected to be very small, however, as discussed in Section 2.1, and are also assumed to be in a dry (non-sticky), solid form. Thus, fouling of the heat exchanger can probably be prevented by allowing sufficient spacing of the tubes and maintaining a high enough velocity to keep the particles entrained in the gas stream. Erosion is also not expected to present a major problem since the particles would be very small.

### 3.1.2 Review of Current Applications and Development Programs

With these design considerations in mind, a review of current ceramic recuperator applications and development programs was made in order to identify the most promising concepts for this application.

Several ceramic recuperators are available as commercial products; other versions are undergoing development. These fall into various categories that are indicative of the applications and of the capabilities of ceramic fabricating technology. A good overview of ceramic recuperators is available in a survey paper by C. F. McDonald (Ref. 28).

One type of ceramic recuperator uses a matrix that consists of an assembly with several heat exchanger passages formed as a single unit, analogous to a metallic plate-fin heat exchanger. This type of core is an extension of the glass matrix such as that built by Corning Glass for the rotary regenerator contemplated for vehicular gas turbines. These recuperators are compact (low fin height and high fin count per inch) and have been designed to withstand a significant pressure difference. The core can be formed from a variety of materials including glass, silicon nitride, silicon carbide, and magnesium aluminum silicate (cordierite). GTE-Sylvania Inc. has developed a formed plate module of cordierite rated for hot gas inlet temperatures of 1640 to 1760 K (2500 to 2700 F). This unit is used, under license, as the core of the "Cuberator" marketed by Thermal Transfer

Corporation (Refs. 29, 30 and 31). Coors Porcelain Co., Corning Glass Works, and the Norton Company have also fabricated modular "plate-fin" elements. A German silicon nitride recuperator of this type is described in Refs. 32 and 33. Experimental results at internal pressure reported in Ref. 32 showed plate rupture occurring at a pressure difference of 3 atm.

The problems associated with the formed-plate module concept make it an unlikely candidate for the MHD application. Dirty gas becomes a serious problem in the small flow passages. The 6 atm pressure is high relative to the state-of-the-art and could result in excessive leakage due to internal cracking of the "plates" and excessive leakage through the mechanical seals around the periphery of the ceramic module.

Another type of design is a "cemented" stacked brick matrix with separated flow packages in each brick element as described in Ref. 34. The design (by Didier-Werke A. G.) described in Ref. 34 is a large unit with large flow passages for use on glass melting furnaces. However, it is limited to nearly equal fluid pressures and applications tolerant of significant leakages.

Effort toward accommodating similar large scale applications with less leakage at slightly higher pressure differentials has led to tubular designs. There are a number of manufacturers of these units for use in such applications as steel industry soaking pits. They typically use large diameter (127-209 mm, (5-9 in.) O.D.) silicon carbide tubes with a cross-flow arrangement. Development of an English design of this type is reported in Ref. 35. The tube-to-heater connection uses a fibre packing type of seal. The typical unit has only a few (less than 100) tubes and the seals can be periodically repacked as part of normal maintenance. Cruciform inserts have also been developed to augment the low inside-the-tube heat transfer coefficient. A "high pressure" unit of this type would have up to 1% leakage at a pressure differential of 4 kPa (16 in. of water). Other information on these designs is given in Refs. 36 and 37. These designs are large scale and could accommodate dirty gases, but cannot be used directly in the MHD application because of the 6 atm oxidant pressure.

Significant development work is now being done with regard to materials, surface forms, and fabrication for tubular heat exchangers for industrial gas turbine

applications. They generally use a cross-flow arrangement with ribbing and other forms of surface roughening for heat transfer enhancement on tubes as small as 25 mm (1 in.) in diameter. Various techniques are used to make the tube-to-header joint.

Extensive literature has been published on the Hague International designs, for example Refs. 38, 39, and 40. Hague's CerHx product line uses silicon carbide tubes with optional external finning and is designed for low pressure applications such as slot furnaces. In Ref. 39, Hague reports a design for a gas turbine cycle with a 6 atm compressor pressure that uses a 95 mm (3.7 in.) O.D. externally finned tube. This is a proposed unit that is of large scale. A design similar to this would be a candidate for the MHD application.

The Department of Energy and EPRI have funded development work on designs for gas turbine applications. Rockwell International, Rocketdyne Division has been performing studies and conceptual designs as part of its "Advanced Coal-Fueled Combustor/Heat Exchanger Technology Study," Ref. 41. Solar Turbines International completed testing of a full-size recuperator module having silicon carbide tubes of 25 mm (1 in.) O.D. and 4.6 m (15 ft.) length. This design used an Inconel 800H header and Inconel 718 bellows at the cold end (Ref. 42). Significant basic work on joining technology has also been reported (Refs. 43 and 44). AiResearch Manufacturing Co. of California has reported experimental data on a prototype U-tube design for gas turbine cycles. Information on this work is given in Refs. 45-48. None of the high pressure units has been developed to the point of commercial availability.

Of all ceramic recuperative heat exchanger designs and design concepts, only some of the low pressure differential designs (of the order of 5 kPa, or 20 in. of water) are commercially available. The high pressure designs (up to 6 atm in the high pressure side) are in early development stages. Based on the work done to date, the most likely surface is a silicon carbide tube. These tubes are commercially available with operating temperatures higher than the MHD ITOH requirement. Finned tubes have been manufactured, but would be likely to become fouled by the particulate-bearing gas stream.

The conceptual design presented in the following section was based primarily on the AiResearch prototype design (Refs. 45-48). In the AiResearch work, small U-

tube and manifold assemblies were fabricated. These assemblies were tested at high temperatures in the presence of coal slag. Pressure containment at 1505 K (2250 F) and 3.4 MPa (500 psia) and resistance of the silicon carbide material to erosion and corrosion by the coal slag were demonstrated. Extension of the ceramic joint and assembly concepts to large sizes will require additional development work, however.

A major advantage of a ceramic recuperator, as opposed to a periodic flow regenerator, is that flow sequencing valves and controls are not required in order to achieve continuous flows of MHD gas and oxidant. A constant temperature would be achievable, thus eliminating the ripple associated with a fixed bed regenerative heater. However, if frequent repairs become necessary, valves and controls may be needed to isolate the various heater modules. In this design study the optimistic view was taken that isolation valves would not be needed. It is assumed that minor tube or joint failures and the resulting leakage would be tolerable in the heater operation.

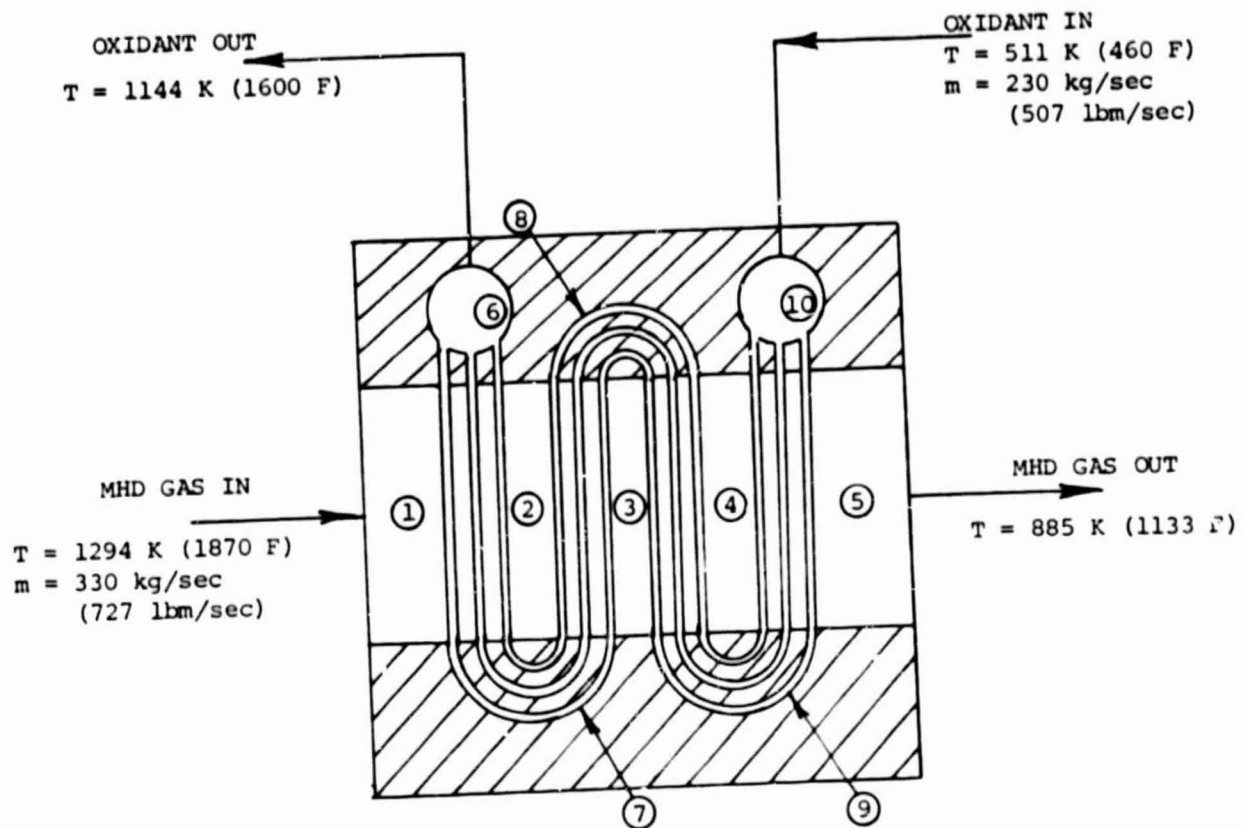
### 3.2 Conceptual Design

The heater system process diagram is shown in Fig. 12. The oxidant inlet and outlet temperatures, the MHD gas inlet temperature, and the MHD gas and oxidant flow rates are as specified. The temperatures indicated in Figure 12 at intermediate points in the heater system represent average conditions for the modules, accounting for system heat losses. No allowance was made for leakage of oxidant into the MHD gas stream.

#### 3.2.1 Heater System Configuration

The heater system consists of 20 individual modules and the necessary MHD gas and oxidant ducts and manifolds to distribute the flow. The configuration of a module is shown in Fig. 13. The ceramic tube and header assembly is shown in Fig. 14. The heater system configuration is shown in Figs. 15 and 16, which illustrate the arrangement of the MHD gas ducts and manifolds and the oxidant ducts and manifolds, respectively. Heater system parameters are summarized in Tables IX and X.

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$T_{\text{MHD Gas}}$			$T_{\text{Oxidant}}$		
LOCATION	K	(F)	LOCATION	K	(F)
1	1283	(1850)	6	1147	(1604)
2	1218	(1732)	7	1040	(1412)
3	1134	(1581)	8	904	(1167)
4	1028	(1390)	9	730	( 854)
5	892	(1146)	10	509	( 456)

FIGURE 12. PROCESS DIAGRAM FOR CERAMIC RECUPERATIVE HEATER SYSTEM

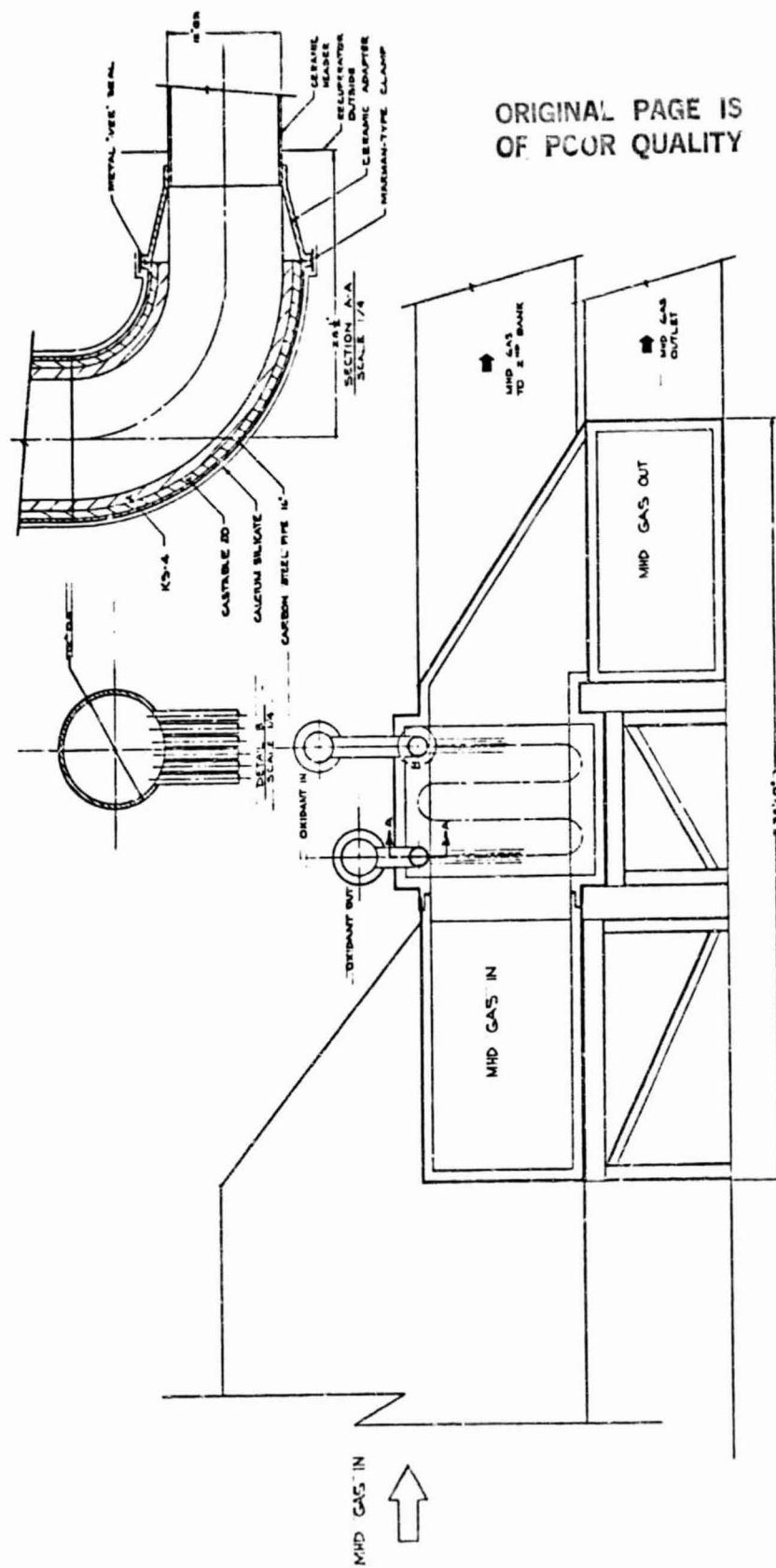
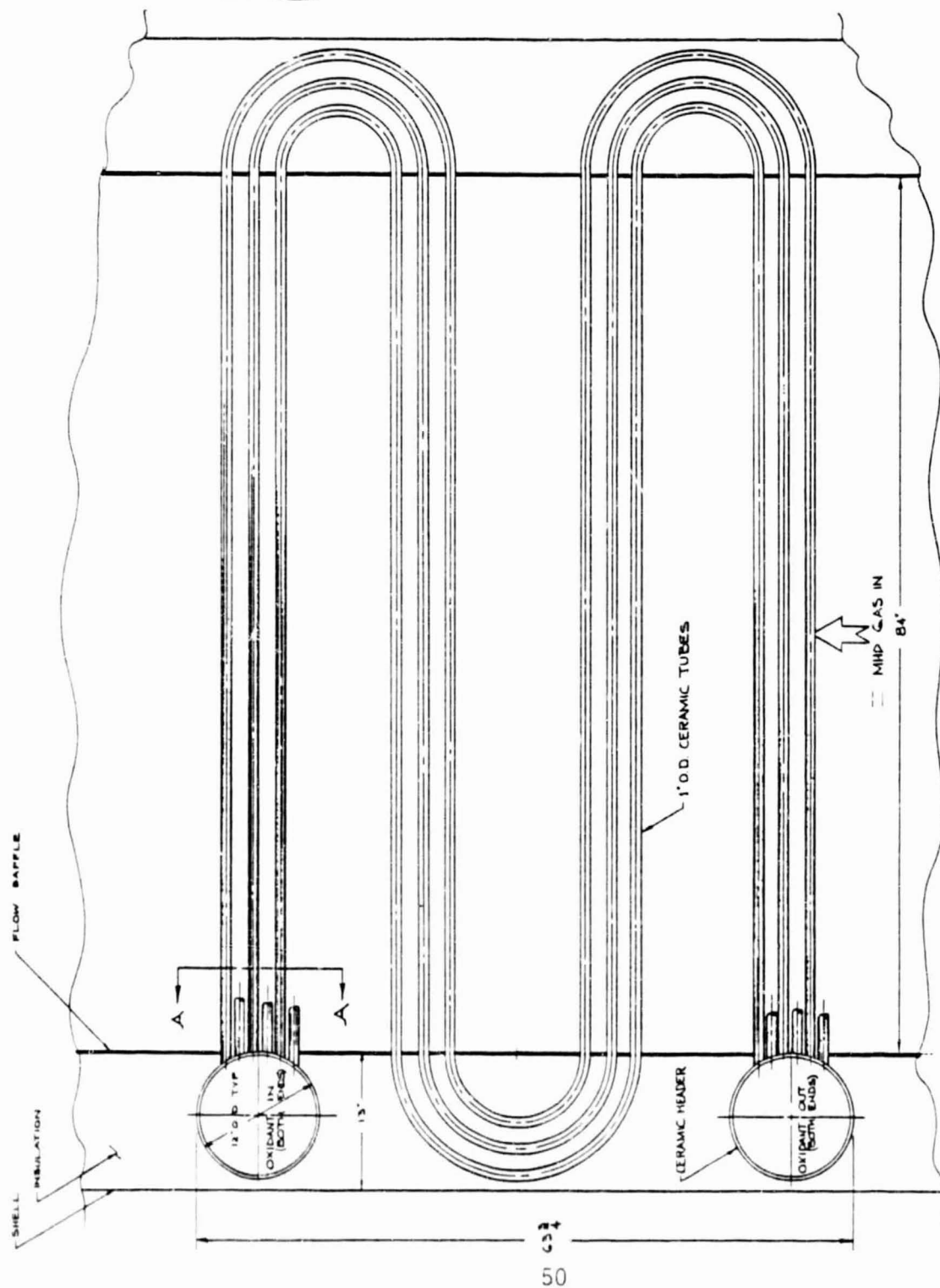


FIGURE 13. ELEVATION VIEW SHOWING INDIVIDUAL RECUPERATOR MODULE CONFIGURATION





VIEW A-A  
SCALE 1/4\"/>

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FIGURE 14. CONFIGURATION OF CERAMIC TUBE ASSEMBLY



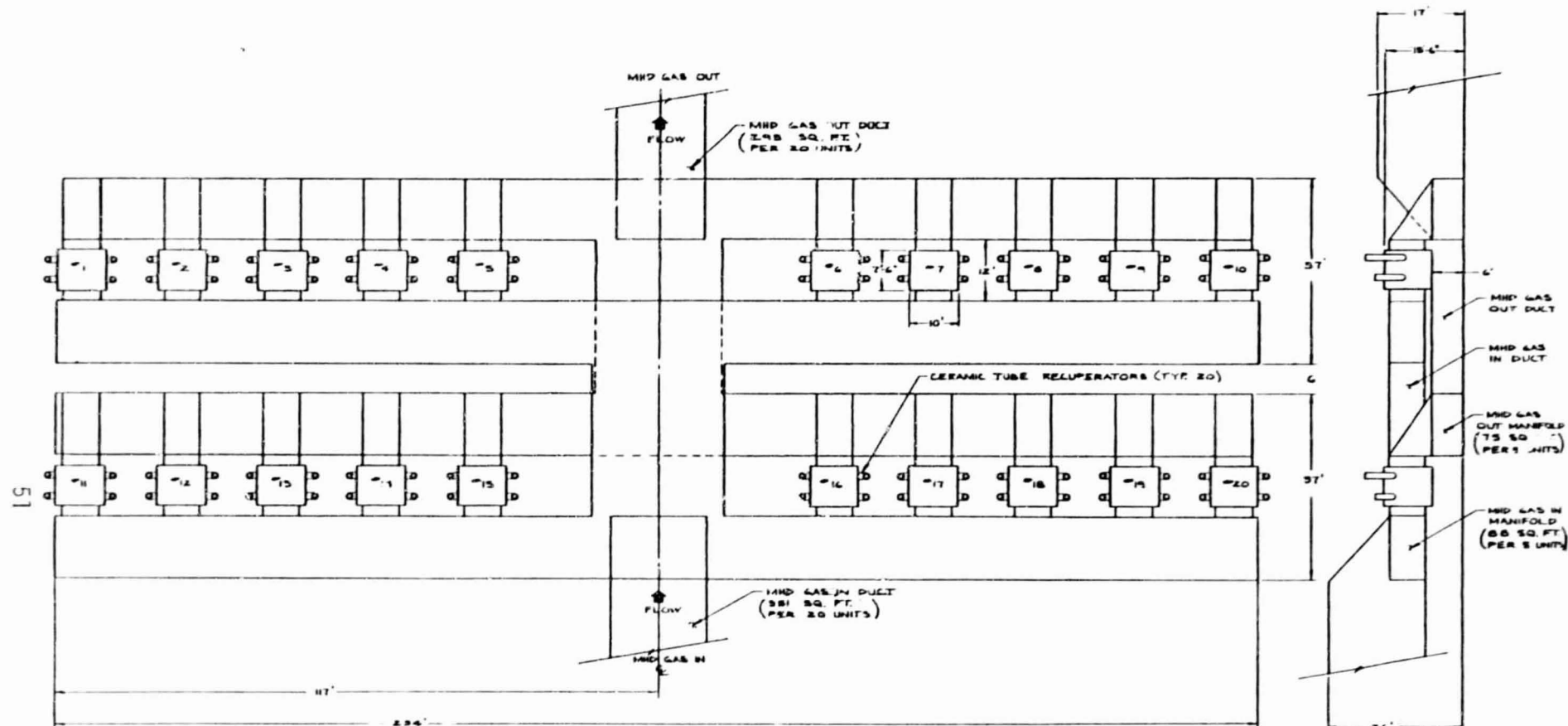
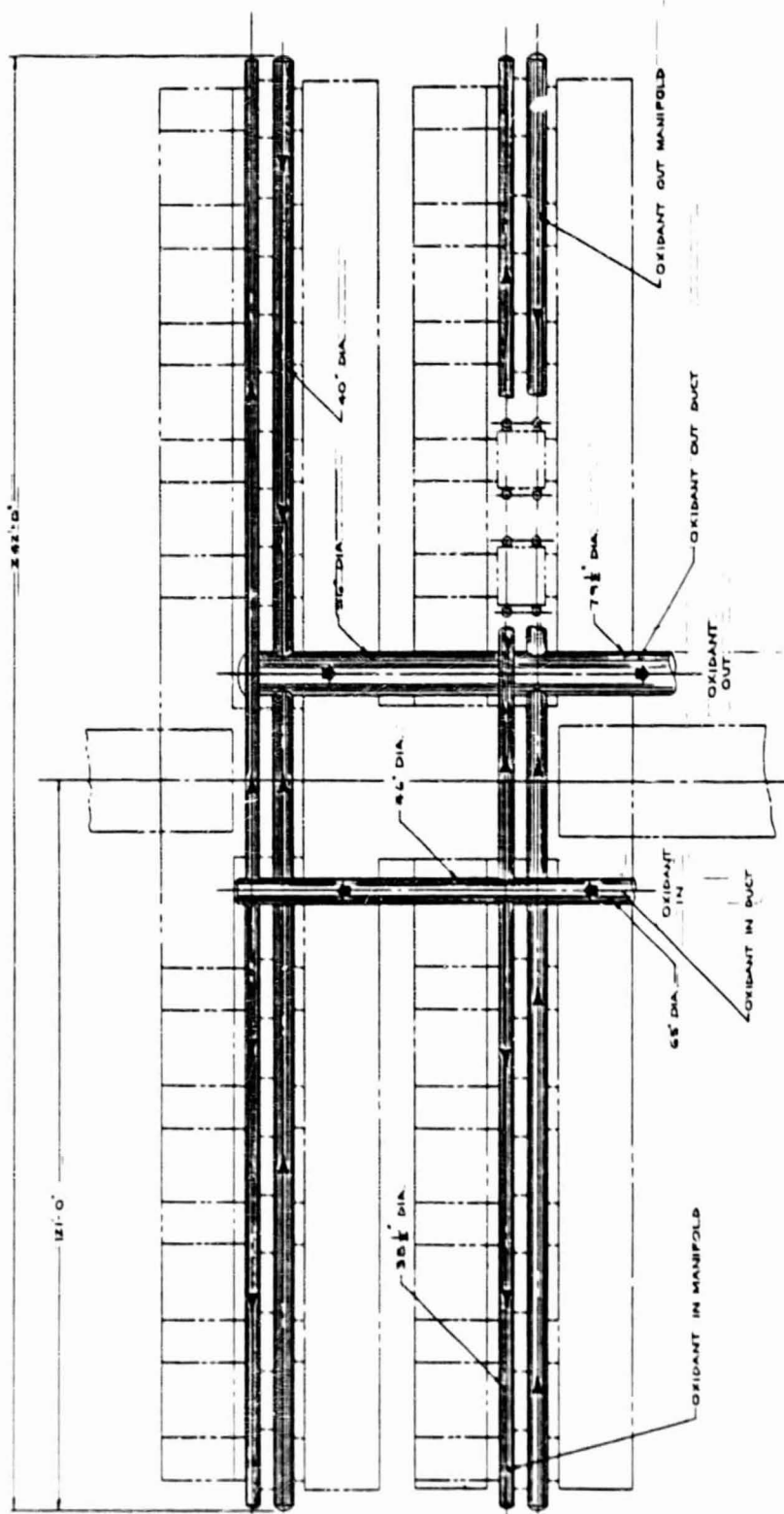


FIGURE 15. HEATER SYSTEM CONFIGURATION SHOWING MHD GAS DUCTS AND MANIFOLDS

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FIGURE 16. HEATER SYSTEM OXIDANT DUCT AND MANIFOLD CONFIGURATION

TABLE IX - CERAMIC RECUPERATIVE HEATER SYSTEM PARAMETERS

CONFIGURATION AND DESIGN PARAMETERS	
General Arrangement:	4 Pass Cross-Counterflow
No. of Recuperator Modules:	20
Tube Diameter:	25.4 mm (1 in.) O.D.
Tube Wall Thickness:	3.2 mm (1/8 in.)
Tube Arrangement:	Staggered, 6 rows in direction of MHD gas flow - each module
Tube Row Spacing:	31.75 mm (1.25 in.) center-to-center (both normal and parallel to flow)
Active Tube Length:	2134 mm (84 in.) - each pass
Number of Tubes/Module:	477 - each pass
Ceramic Header Diameter:	305 mm (12 in.) O.D.
Ceramic Header Wall Thickness:	6.35 mm (1/4 in.)
Active Header Length:	2540 mm (100 in.)
Tube/Header Material:	Norton NC430 Silicon Carbide
SYSTEM PERFORMANCE PARAMETERS	
MHD Gas Pressure Loss:	4.2 kPa (0.61 psi)
Oxidant Pressure Loss:	20.0 kPa (2.9 psi)
System Heat Loss:	6.4% of Heat Duty

TABLE X - CERAMIC RECUPERATIVE HEATER SYSTEM DUCT AND MANIFOLD CONFIGURATIONS

ITEM	MAX. FLOW DIMENSION	INSULATION THICKNESS		
		Layer 1 <sup>1</sup> mm (in.)	Layer 2 <sup>2</sup> mm (in.)	External <sup>3</sup> mm (in.)
MHD Gas Inlet Duct	32.6 m <sup>2</sup> (351 ft <sup>2</sup> )	63.5 (2.5)	88.9 (3.5)	12.7 (0.5)
MHD Gas Inlet Manifolds	8.2 m <sup>2</sup> (88 ft <sup>2</sup> )	63.5 (2.5)	88.9 (3.5)	
MHD Gas Outlet Duct	27.4 m <sup>2</sup> (295 ft <sup>2</sup> )	63.5 (2.5)	31.8 (1.25)	
MHD Gas Outlet Manifolds	7.0 m <sup>2</sup> (75 ft <sup>2</sup> )	63.5 (2.5)	31.8 (1.25)	
Oxidant Inlet Duct	1.65 m (65 in.) dia.	----	----	
Oxidant Inlet Manifolds	.98 m (38.5 in.) dia.	----	----	
Oxidant Outlet Duct	2.02 m (79.5 in.) dia.	63.5 (2.5)	69.8 (2.75)	
Oxidant Outlet Manifolds	1.02 m (40 in.) dia.	63.5 (2.5)	69.8 (2.75)	

<sup>1</sup> High Strength Fireclay Castable (KS-4)

<sup>2</sup> Insulating Castable (C-20)

<sup>3</sup> Calcium Silicate

The basic heat exchanger module consists of a four pass, cross counterflow silicon carbide tube assembly. The four passes are made by straight 25.4 mm (1 in.) outer diameter tubes with 3.7 mm (1/8 in.) wall thickness. The straight tubes are joined by silicon carbide U-tubes of similar diameter and wall thickness, and the tube assembly is joined to a silicon carbide header at each end. The design was developed so that the length of the straight tubes would not exceed 3 m (10 ft.), and the ceramic header sizes were limited to 305 mm (12 in.) diameter and 2540 mm (100 in.) length. The tube spacings were also chosen so that no U bends had a turn radius/tube diameter less than 5.5 to keep stresses at a reasonable level. These size and spacing limitations were determined on the basis of reasonable expectations of future silicon carbide manufacturing capabilities and on the pressure containment requirement. Finned tubes were not selected because of the potential for fouling due to the particulate loading in the MHD gas stream.

A ceramic/metal joint is made at the ends of each silicon carbide header. The joint is illustrated in Fig. 13 and consists of a flanged, conical ceramic section which is attached to the metallic pipe with a Marman type clamp, following the method described in Ref. 45.

The ceramic headers and the U-tube portions of the tubular assembly are enclosed by the metallic recuperator module shell and surrounded by insulation. A "baffle" consisting of a thin sheet of high alloy steel separates this insulation layer surrounding the ceramic headers and U-tubes from the MHD gas flow. Since its only function is to minimize flow bypassing of the active heat exchanger tubes, this baffle will not require high strength and therefore some degree of corrosion of the baffle material will not pose a serious problem.

As shown in Figure 15, the heater system is arranged with the main MHD gas inlet and outlet ducts on a common centerline. Four sets of inlet and outlet manifolds run perpendicular to the main ducts as shown in Figure 16, to distribute flow to, and collect flow from, four legs having five heater modules each. The oxidant inlet and outlet ducts run parallel to the MHD gas ducts, one on each side of the gas ducts. Oxidant manifolds run perpendicular to the main ducts and above the individual recuperator modules. Two vertical pipes extend downward from the oxidant manifolds to provide a connection at the ends of each

ceramic header. Proper distribution of the flows through the heater system would be assured by appropriate considerations in the preliminary and final design phases.

The insulation materials and thicknesses for the MHD gas and oxidant ducts and manifolds are summarized in Table X. A layer of extra strength fireclay castable for erosion resistance and a second layer of a moderate temperature insulating castable are used to internally insulate the metallic gas inlet and outlet ducts and manifolds and the metallic oxidant outlet manifolds and duct. The oxidant inlet duct is not internally insulated. All of the metallic ducts and manifolds and the recuperator module shells are covered with a calcium silicate type external insulation.

The heater system would be field fabricated, with the exception of the ceramic header-tube assemblies which would be shop fabricated and installed as complete units.

As noted previously, the ceramic recuperator would require considerable development effort as well as expanded manufacturing capabilities in order to produce the required ceramic components. Lifetimes of the vessel and duct refractory linings on the order of 15-20 years should be achievable. Estimates of life for the silicon carbide assemblies cannot be made at this time due to the early development stage of the technology.

Details of major heater system components and heater system operation and performance are discussed in the following sections.

### 3.2.2 Design Approach

A description of the approach used to develop the conceptual designs for the major heater system components is given in the following paragraphs.

#### Sizing Methods

The heat exchanger matrix was sized by using a Fluidyne computer program previously developed for analysis of multiple-pass cross-counterflow heater

designs. The computer program was used to determine the tube bundle dimensions required to meet the specified thermal performance and allowable pressure losses.

The computer program utilizes an iterative solution procedure to solve the algebraic heat exchanger sizing equations (Ref. 49). Frictional losses, entrance and exit effects, losses due to flow acceleration, and turning losses are computed. Thermal/hydraulic performance data from Ref. 49 are used. The relationship between heat exchanger effectiveness and number of transfer units for cross flow is based on a series solution developed by Mason (Ref. 50). The computer solution is based on bulk mean fluid conditions.

Several parameters were considered for the heater system conceptual design, including tube diameter, oxidant inside or outside the ceramic tubes, pressure loss, heat exchanger shape, tube spacing, and various single or multiple pass cross counterflow configurations.

#### Number of Heater Modules

Multiple heater modules are required in order to provide the necessary heat transfer surface area while still meeting various restrictions placed on the size of the ceramic components. The choice of 20 individual units resulted from the various size restrictions assumed, as discussed above. Other assumptions could be made regarding allowable sizes, which would have some impact on the number of individual heater modules. However, the sizes used in this conceptual design represent extensions to present manufacturing capabilities for ceramic components capable of the required pressure loading, and further extensions did not seem justified on the basis of ceramic recuperator experience to date.

#### Ceramic Assemblies

The proposed ceramic material is Norton NC430, a dense, sintered silicon carbide featuring a bimodal grain size distribution of high purity silicon carbide. It is impregnated with metallic silicon to close any residual porosity. This material has been used at temperatures up to 1670 K (2590 F) and, as discussed previously, has been shown to have good erosion and corrosion resistance in the presence of coal slag (Ref. 45).



The concept envisioned for fabricating the manifold/tube assemblies illustrated in Fig. 14 is as follows. The manifolds, straight tubes, and U-tubes would be cast and fired separately. These components would then be joined with additional "green" silicon carbide material, and the entire assembly would be fired to produce a pressure containing unit. The proposed quantity and length of straight tubes as well as the diameter of the ceramic manifolds exceed current manufacturing capabilities (Ref. 45). Thus, manufacturing capabilities would need to be developed. A furnace large enough to fire the entire assembly would also need to be developed. The required development work and extrapolation of manufacturing capabilities are expected to be feasible if a sufficient market demand were to exist.

Other methods for fabricating silicon carbide structures and joining techniques such as the relaxing joint under development by Solar Turbines International (Refs. 43 and 44) should also be considered. However, an exhaustive survey of ceramic fabrication techniques was beyond the scope of this conceptual design study, and the presented fabrication procedure was selected as a reasonable method for the basis of the design.

#### Tube and Ceramic Header Arrangement

Tubes in each pass through the MHD gas are arranged in a staggered fashion relative to the MHD gas flow direction. Tube spacing from row to row is 31.75 mm (1.25 in.) center-to-center both parallel and normal to the flow direction as shown in Figure 14. Six rows of tubes, in the direction of the MHD gas flow, are used in each pass. The tubes are suspended vertically from the two ceramic headers in each assembly, and the ceramic headers are supported by hangers from the roof of the heater module vessel. This arrangement allows for thermal movement of the individual tubes without developing large stresses. Each ceramic header is fed by, or discharges to, the larger metallic air inlet or outlet manifolds at both ends. The velocities in the ceramic headers were restricted to values about equal to the velocities in the individual tubes.

It is felt that the selected tube spacing will be sufficient to prevent accumulation of the small particulate matter in the heater system. Should further design efforts indicate a need, a sootblowing system could be accommodated in



the presented design. Larger tube spacing would then be required, and design precautions would be required to avoid thermal shock problems. These considerations would add to the heater system cost.

### Thermal Insulation

The insulation materials and arrangements chosen for the heater modules, metallic manifolds and ducts are the same as for the fixed bed regenerative heater system. The maximum service temperature is moderate so that the vessel duct and insulation scheme is straightforward. Inexpensive, highly thermal resistive castable refractory attached by metallic anchors can be used. The design parameters for insulation sizing were a nominal surface heat flux of  $1340 \text{ W/m}^2$  ( $425 \text{ Btu/hr. ft}^2$ ), or an outer skin temperature of approximately  $390 \text{ K}$  ( $250 \text{ F}$ ). A nominal steel vessel temperature of  $480\text{--}530 \text{ K}$  ( $400\text{--}500 \text{ F}$ ) was selected to prevent corrosion due to  $\text{NO}_x$  or  $\text{SO}_x$  species. External insulation was specified in order to maintain the necessary steel vessel temperature. A liner using a high strength fireclay castable was selected to provide erosion resistance. A thickness of  $63.5 \text{ mm}$  ( $2.5 \text{ in.}$ ) was selected as the minimum for simple installation procedures. Where appropriate, a second insulating layer of the equivalent of Harbison Walker Castable 20 was used to reduce total insulation costs. The air inlet ducts and manifolds are not internally insulated. The types of insulation and the thicknesses of the layers used in the various locations are indicated in Table X and Appendix E.

The estimated heat loss for the heater system is  $6.4\%$  of the heat duty. A heat loss vs. system cost trade-off was not made because of the limited scope of the conceptual design. Optimization would have a minor effect on total system cost.

#### 3.2.3 Heater System Operation and Performance

The heater system will provide continuous flows of MHD gas and oxidant at the temperatures shown in Fig. 12. The temperatures at intermediate points in the heater system were calculated, accounting for system heat losses. These values represent the average performance of the 20 heater modules. No attempt was made to estimate performance variations due to maldistribution of flows through the heater system. Appropriate steps to minimize maldistribution would be made in preliminary and final design phases.

The conceptual design does not include a control system. None is required to maintain the heater performance. If, however, leakage through the ceramic components and joints should prove to be significant or if modules must be periodically isolated for adjustment or repair, some degree of control will be required to maintain the heater system performance. Determination of the extent of need for some degree of control, as well as the need for spare modules and/or excess system capacity, will be dependent upon the development of ceramic recuperator technology and on component reliability and availability requirements.

### 3.3 Cost Estimate

A cost for the ceramic recuperative heater system described above was estimated. The estimate which includes cost of materials, fabrication and installation, is \$15,824,000 in 1980 dollars. A summary of the costs by major component is given in Table XI.

The major cost component in the heater system is the ceramic header/tube assemblies. This is also the item having the major cost uncertainty since the fabrication technology is an unknown factor at this time. Thus it is evident that any judgement as to the economic viability of the ceramic recuperator will require better information on the cost of this component.

The basis for the cost estimate is discussed in the following sections, and a detailed cost breakdown is provided in Appendix E.

#### 3.3.1 Basis for Cost Estimate

Costs were estimated using the following general guidelines:

- The costs of all materials, shop fabricated components, and purchased equipment are F.O.B. manufacturer's plant, i.e. ready-to-ship. No shipping costs from manufacturer to site are included.

TABLE XI - CERAMIC TUBE RECUPERATIVE HEATER SYSTEM ESTIMATED COST

COMPONENT DESCRIPTION	COST \$1,000's
Recuperator Modules (20)	
Steel Shell	274
Refractory Insulation (installed)	294
Ceramic Header/Tube Assembly	<u>7460</u>
Total Recuperator Modules	8028
MHD Gas and Oxidant Ducting (with installed insulation)	3803
Major Expansion Joints and Miscellaneous Parts	348
Support Structure and Foundations	600
Erection and Assembly (excluding refractory installation but including silicon carbide header/tube installation)	<u>3045</u>
TOTAL HEATER SYSTEM	15824

- Rates for field labor or shop labor are based on \$42 per hour which includes direct wages and indirect charges such as supervision, insurance, fringe benefits, workers compensation, support staff, tools and equipment, contingency and contractor fee or profit. This rate is converted to a basis of dollars per pound or dollars per cubic foot in some instances.
- Engineering design costs are not included.
- Indirect costs and contractor profit or fee have not been specifically added to the costs for purchased components but are included through the application of the labor rates specified above.
- Costs were established directly from the weights, volumes, or capacities of the components listed.
- In the cases of structural steel and field erection and assembly, quantities or costs were estimated as percentages determined from previously installed test facilities and ceramic heaters designed by Fluidyne or from previous studies of ceramic heaters.

### 3.3.2 Steel Components

Material and fabrication cost rates for the types of steel used in the system are given in Table VI.

### 3.3.3 Refractory Materials

The cost rates for the types of refractories included in the facility are given in Table XII. Factors are applied to account for rebound (loss of castable material when gunning onto a surface), for anchors to hold the castable material in place, and for supporting the external installation.

TABLE XII - ESTIMATED COSTS FOR REFRACTORY MATERIALS

LOCATION	Refractory Type	Material Cost (\$/lb)	Adjusted Material Cost, Incl. Rebound Anchor, or Support port Factors (\$/lb)
Ducting & Piping	Castable, C-20	.46	.60
	Castable, KS-4	.214	.28
External Insulation	Calcium Silicate	1.00	1.05

TABLE XIII - ESTIMATED INSTALLATION COSTS FOR REFRACTORY MATERIALS

Refractory Category	Complexity Factor (Multiplier)	Installation Cost Rate (\$/ft <sup>3</sup> )
External Insulation	0.7	22.72
Castable Material	0.8	26.00
Large Horizontal Ducts	1.0	32.50

### 3.3.4 Refractory Installation

Refractory installation costs are based on the following determination of cost per unit volume of installed refractory:

- There are 17.2 nine inch equivalents (equal to the volume of a standard 9" x 4.5" x 2.5" refractory brick) in to one cubic foot.
- Labor hours required per nine inch equivalent are
  - .0375 hours/9 in. equivalent (for installation)
  - .0075 hours/9 in. equivalent (for materials handling)
  - .0450 hours/9 in. equivalent

Therefore the basic installation cost rate is:

$$(.0450) (17.2) (42) = 32.50 \text{ \$/ft}^3$$

This installation rate is multiplied by complexity factors, some of which reduce the rate and some of which increase the rate. Typical complexity factors are given in Table XIII.

### 3.3.5 Silicon Carbide Assemblies

The tube and ceramic header costs were determined primarily on the basis of information from Ref. 45. An extrapolated cost (five to ten years in the future) for straight tubes of impervious silicon carbide of \$4-6/lb was given by the manufacturer, assuming a large production rate. Twenty percent of this cost was attributed to materials and the remaining 80% was attributed to fabrication and firing. Thus, the estimated fabrication and firing costs amount to 4 times the material cost. The assembly envisioned for the conceptual design involves fabrication of straight tubes, U-tubes, and headers of silicon carbide; these are then joined and fired again into a single unit. This operation will involve careful handling, assembly of furnace supports, and firing in a large furnace. The approach chosen for the cost estimate was to establish costs for the straight tubes (based on Ref. 45), U-tubes, and headers (based on information obtained from discussions with an industrial ceramic recuperator designer). A fabrication and firing cost was then determined using a similar factor of 4 applied to these costs, based on the above information from Ref. 45.

### 3.3.6 Expansion Joints

It was assumed that expansion joints would be required on both ends of the two headers in each recuperator unit. It was also assumed that the oxidant inlet and outlet manifolds would each require an expansion joint per recuperator unit. Recent quotations from manufacturers on similar size joints were used to establish the expansion joint costs.

### 3.3.7 Erection and Assembly

An amount equal to 25 percent of the total cost of all materials, shop fabricated components, purchased equipment and refractory installation (excluding the support structure and foundations) was included for erection and assembly of the system. This percentage was based upon FluidDyne's experience in the erection and assembly of large wind tunnel facilities. The 25% rate seems justified in this case since special techniques will need to be developed for the handling and assembly of the recuperator elements. It is also probable that a large amount of mobile crane time will be required to erect the system, which also contributes to the size of the percentage.

#### 4.0 ENGINEERING ASSESSMENT OF MOVING BED REGENERATIVE HEATER

An engineering assessment of the moving bed regenerative heater for the MHD oxidant heater application was made. A survey of moving bed heater applications was conducted, and advantages, disadvantages, significant design considerations, and areas for further investigation were identified. This information is presented in the following sections.

##### 4.1 Moving Bed Heater Applications

The concept of a moving bed, continuous flow heat exchanger (or moving pebble bed) involves one or more heater vessels having upper and lower chambers, through which ceramic beads or pebbles flow slowly, driven by gravity. The pebbles would be heated by the MHD exhaust gas in the upper chamber. In the lower chamber, the pebbles would give up heat extracted from the MHD exhaust gas and transfer it to the oxidant being heated.

The moving bed concept has been known for many years. Reference 51, published in 1946, describes the moving pebble bed heater concept and a design to heat air from ambient temperature to 1530 K (2300 F) as shown in Fig. 17. Few industrial heaters of this type are known, however.

Several examples of industrial applications of the moving bed regenerator concept have been reviewed. Heated ceramic balls are used in the Tosco retorting process to heat oil shale (Ref. 57). The 12.7mm (1/2 in) balls are circulated through a ball heater and a rotary kiln in which the shale is heated to approximately 750 K (900 F). The process is illustrated in Fig. 18. A "dry media heat exchanger" of the moving bed regenerator type is described in Ref. 53. This heat exchanger uses iron foundry cupola exhaust gas to heat air to 810 K (1000F). Fine mesh ceramic particles are used for the circulating medium. An experimental facility is described in Ref. 54 in which a moving bed of granular material is passed over the tubes in a heat pipe heat exchanger to allow operation of the unit in a particulate laden gas stream. All these units operate with little or no pressure difference between the pebble chambers and thus would not be directly applicable to the MHD intermediate temperature oxidant heater.



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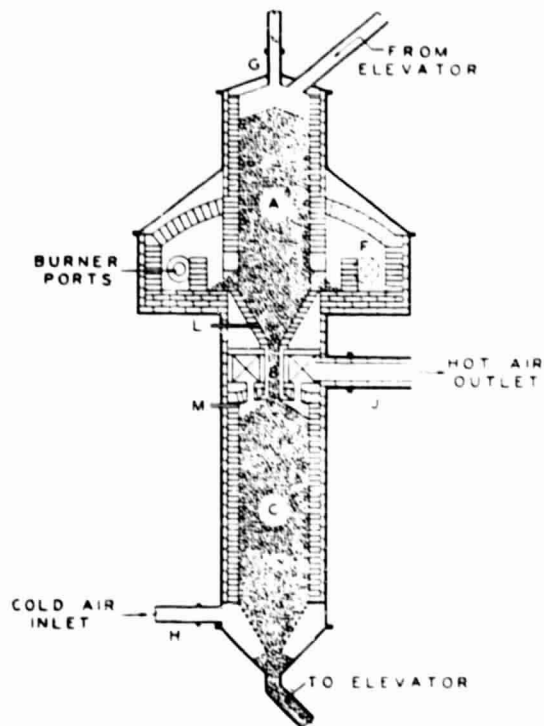
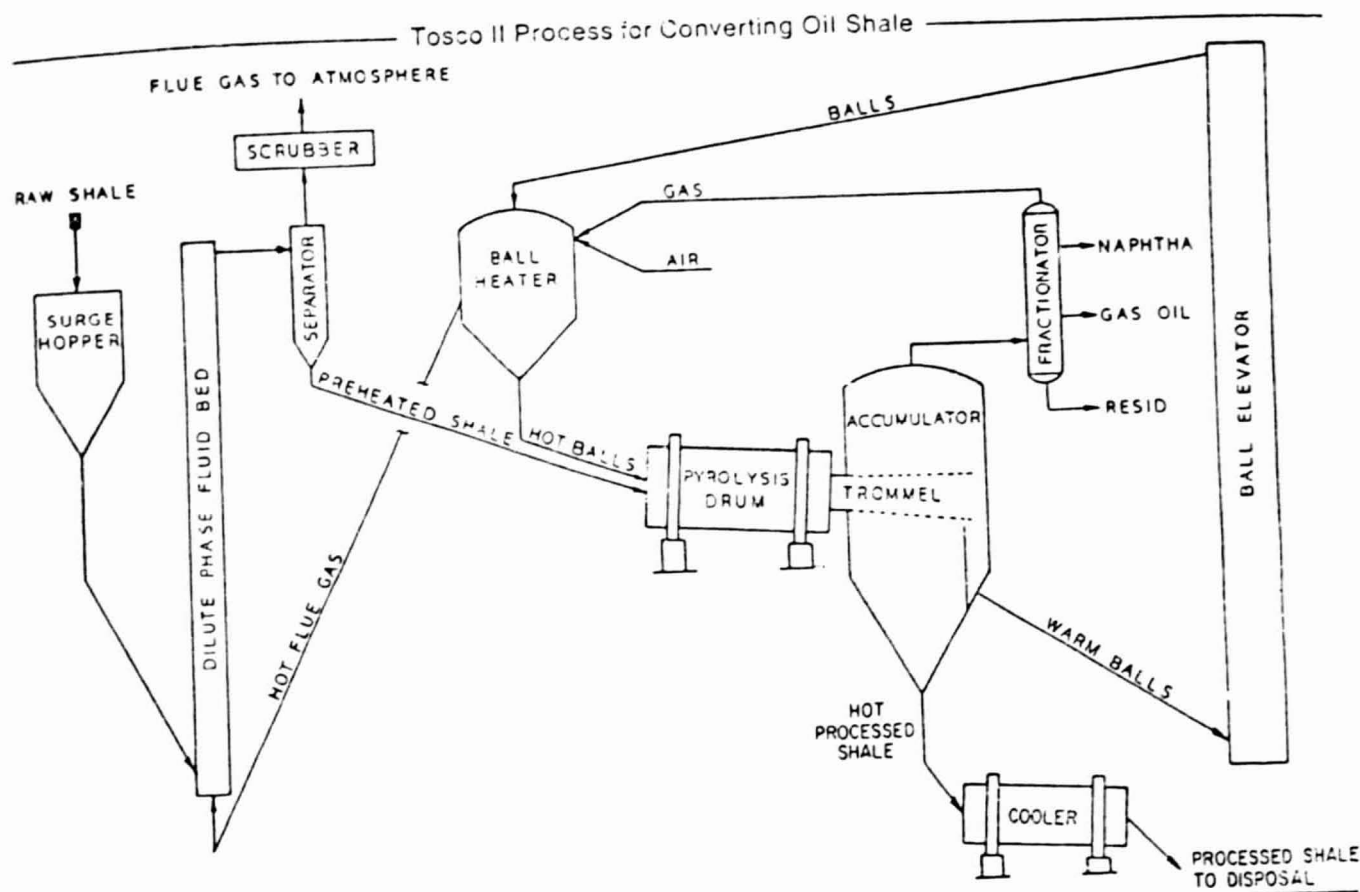


FIGURE 17. MOVING PEBBLE BED HEATER DESIGN  
(From Reference 51)



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FIGURE 18. OIL SHALE CONVERSION PROCESS USING MOVING PEBBLE HEATER CONCEPT (From Reference 52)

Other applications of the moving bed regenerative heater concept are the moving fluidized bed (Ref. 4) and variations on the "falling cloud" concept which use small particles of solid material (Ref. 55) or of liquid material or a material which undergoes a phase change in the heater (Ref. 4). In the moving fluidized bed concept discussed in Ref. 4, the oxidant, after being heated by the fluidized particles in one chamber, flows directly into the combustor. The MHD gas downstream of the channel then flows through the fluidized particles in the other chamber to heat them. The particles are transported from one chamber to another through a separate duct, parallel to the gas flow. No experimental work actually involving a moving fluidized bed was reported in Ref. 4.

The falling cloud concept closely resembles the moving pebble bed; the only conceptual difference is that small particles are used in place of the larger pebbles proposed in Ref. 51. Extensive studies of a regenerator of this type employing liquid slag as the air heating medium (which solidifies in the air heating chamber before being recycled to the slag heating chamber) are reported in Ref. 4. The topics studied included atomization of the high temperature slag, transportation of molten slag from one chamber to another, heat and mass transfer in each chamber, aerodynamic design of the chambers, and transportation of solidified slag. While the temperature level in the intermediate temperature oxidant heater is too low to use liquid slag as the heat transfer medium, much of this work may be applicable in any further work on the moving bed regenerative heater.

A falling cloud heat exchanger using solid alumina or steel particles for heat recovery in various industrial waste gases is discussed in Ref. 55. Several heat transfer and flow experiments conducted at relatively low temperatures (less than 500 K, 440 F) are reported and a pilot plant presently under construction is described. This work also may be applicable to future moving bed regenerator studies, although the intended temperature and pressure levels are modest compared to the needs of the MHD application.

A moving pebble bed heater has been built and operated in Swierk, Poland, as part of the Polish MHD program. The heater design and operation are discussed in Refs. 56-61. This heater was used in MHD experiments for several years to heat air at approximately 2.5 atm to temperatures up to 1400 K (2060 F). The

pressures in the heater were carefully controlled so that no differential pressure existed between the two pebble chambers. The heater was separately fired with clean gas. Figures 19 and 20 illustrate the Polish heater.

The design and operating experience of the Polish pebble bed heater were reviewed. In addition to the information obtained from Refs. 56-61, information was obtained through discussions with Prof. W. S. Brzozowski of the Polish Institute of Nuclear Research.

Development of the Polish moving pebble bed heater was accomplished under a joint Polish-French program. Dr. David Yerouchalmi, then with the French Atomic Energy Commission, participated in the development work. Discussions were held with Dr. Yerouchalmi in the early 1970's regarding the work on moving pebble bed heaters. Notes of these meetings were also reviewed as part of this technical assessment.

#### 4.2 Engineering Assessment

In order to address the technical feasibility of the moving pebble bed concept for the intermediate temperature oxidant heater application, the significant design considerations were studied. Results from the Polish pebble bed heater work was considered where applicable. A schematic representation of the moving pebble bed concept as it might be applied to this application is shown in Figure 21.

##### 4.2.1 Advantages

The major advantages of the moving pebble bed concept for this application are that continuous flow of the MHD gas and oxidant could be maintained without need for flow sequencing valves and the mass of ceramic material required would be significantly less than for a fixed bed regenerative heater. Also, oxidant temperature variation (ripple) is not inherent to the moving bed regenerator as it is in the fixed bed regenerator.

Calculations of the size of the heater using 25.4 mm (1 in.) pebbles showed that a total ceramic pebble mass of 445,900 kg (983,000 lbm) would be required for

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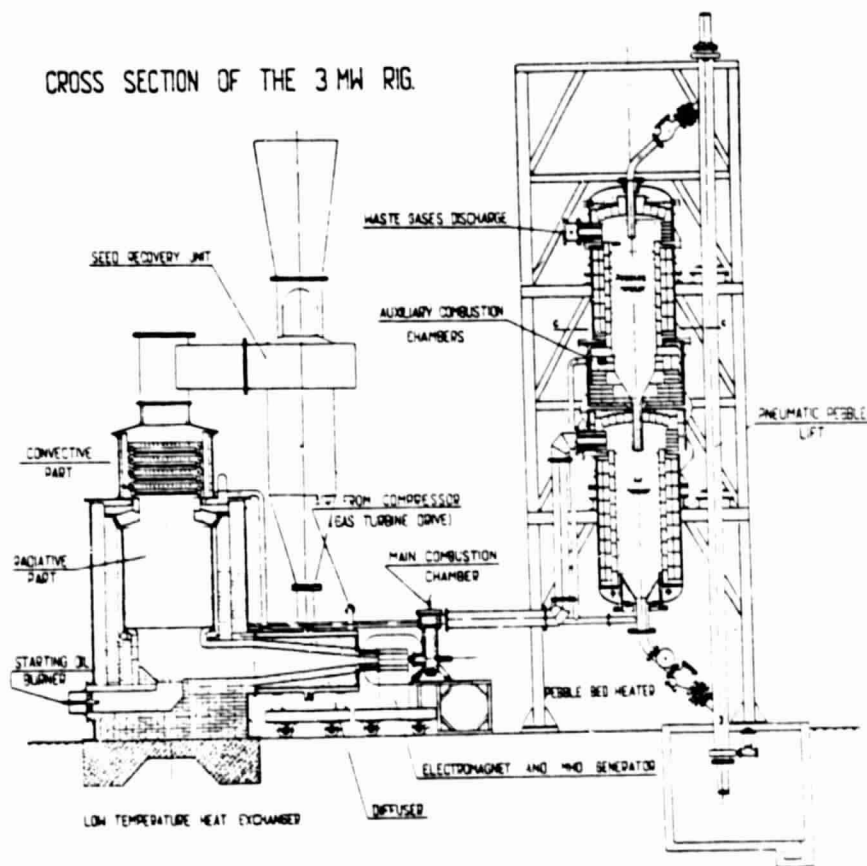


FIGURE 19. POLISH MHD TEST FACILITY SHOWING  
SEPARATELY FIRED MOVING PEBBLE BED  
HEATER (FROM REFERENCE 56)

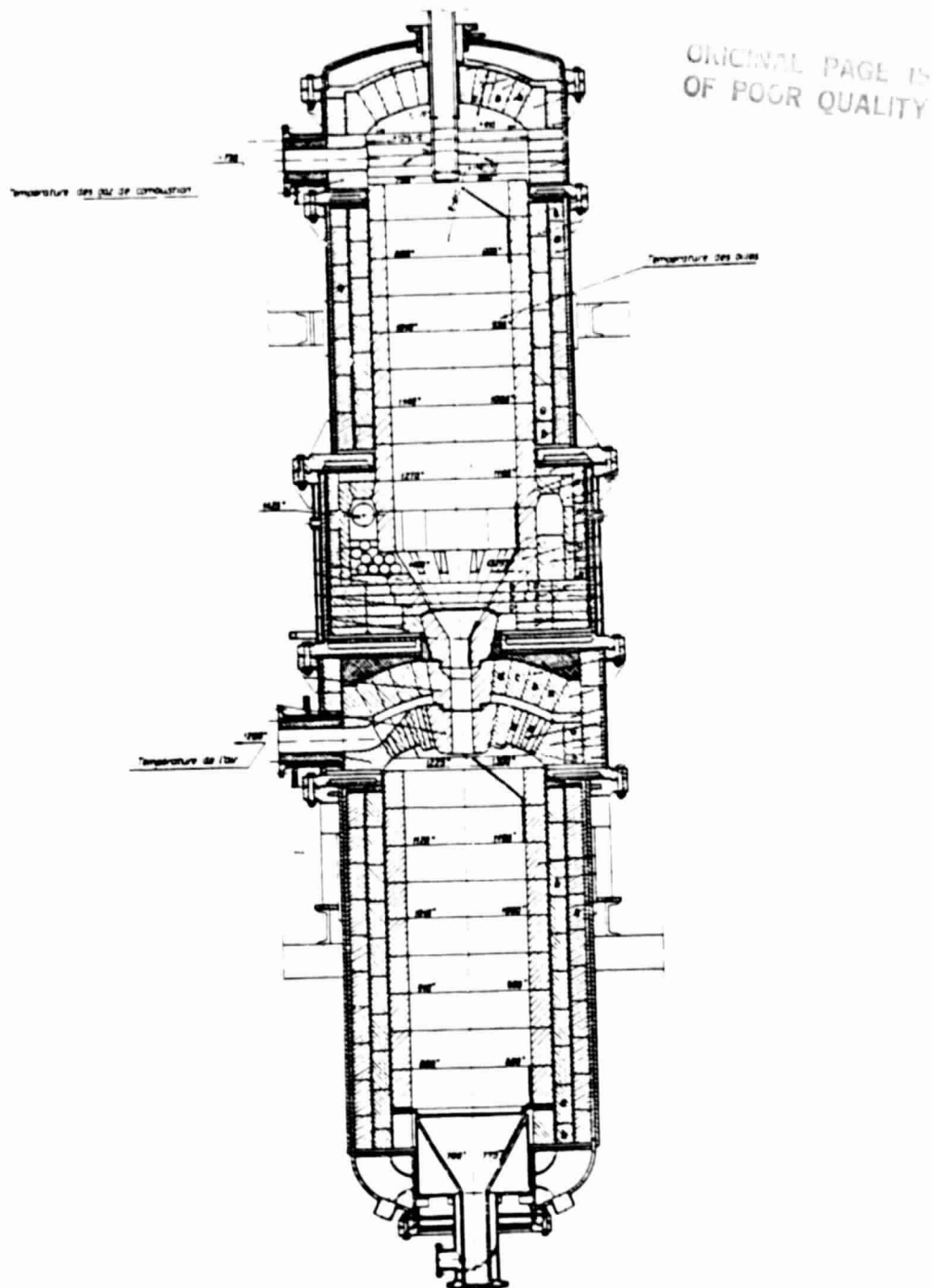


FIGURE 20. CROSS SECTION OF POLISH MOVING  
PEBBLE BED HEATER (From  
Reference 57)

the specified MHD gas and oxidant flows and temperatures. This amounts to 17% of the ceramic mass required for a fixed bed regenerative heater as presented in Section 2.2. The calculations considered rates of heat transfer between the flowing MHD gas and oxidant and the pebbles, frictional losses of the MHD gas and oxidant, heat capacity and thermal conductivity of the pebbles, and the various fluid properties in determining the required heat transfer areas in the two chambers. The calculated pebble mass includes allowance for pebble chamber conical exit plenums and the pebble lift system.

A potential advantage may be that particulate matter could be removed from the MHD gas stream by collecting on the pebbles, reducing the particulate loading for all downstream components.

#### 4.2.2 Disadvantages

In contrast to the fixed bed regenerative type heater, industrial experience with the moving pebble bed type heater is essentially nonexistent. Therefore, a base of standard engineering practice is not available, as opposed to the case of the blast furnace stove for fixed bed regenerative heaters.

The need for ancillary equipment to handle the circulating pebbles represents a major disadvantage of this heater concept. The need for a pressure seal between the two pebble chambers is a problem which may result in similar or even greater cost or complexity than flow sequencing valves, which are not needed, as discussed above.

Another disadvantage of this type heater is that in order to operate the heater with a reasonable pressure drop, the pebble chambers must have a small length/diameter ratio. For example, the heater sizing calculations resulted in an equivalent diameter (if a single chamber were used) of 15.8 m (51.7 ft) for the MHD gas chamber, while the pebble bed height in the gas chamber was 0.2 m (0.8 ft). The corresponding dimensions for the oxidant heating chamber were an equivalent diameter of 8.4 m (27.6 ft) and a bed height of 0.9 m (3.1 ft).

This unusual shape will require careful design to assure proper distribution of gas and pebble flows through the beds; a very large number of small heaters may

be required in order to accomplish this. Therefore, the advantage of a small ceramic pebble mass may be small when compared to the need for large and/or complex air and oxidant gas duct and pebble handling and distribution networks.

In the sizing calculations, the pressure drops across the pebbles in the two chambers were chosen to match the pressure drops across the checker matrix in the fixed bed regenerative heater system. The calculated depths were based on uniform flow of gas and solids throughout the beds; practical considerations would result in deeper beds due to additional entrance and exit regions required to establish uniform flow distributions. Operating with a somewhat larger pressure drop is conceivable, and this would also result in deeper pebble beds. However, the total heater system bed area can not be as small as in the fixed bed heater. This is because the flow resistance in a pebble bed is significantly greater, and the pressure gradient will exceed the pebble weight gradient and float the pebbles if the area becomes too small. (Larger pressure drops would be possible if a fluidized bed concept were used.) Thus the length/diameter ratio can be significantly increased only by increasing the number, and thus decreasing the diameter, of the individual heaters. A heater having the general appearance indicated by Fig. 21 could only be achieved by using a very large number of heaters in the overall system.

The unusual shape of the heater for this application points to the conclusion that the moving pebble bed heater may not be well suited to an application in which the entire gas flow must pass through the heater system. Thus the configuration most suited for this application appears to be one in which only a portion of the total gas flow would be utilized to heat the pebbles. This would result in a more attractive system from the standpoint of physical shape and arrangement.

The potential advantage of particulate removal by the circulating pebbles would be traded for the corresponding need to clean the pebbles as well as for potential fouling of the heated oxidant by particulate matter carried into the oxidant heating chamber by the pebbles.



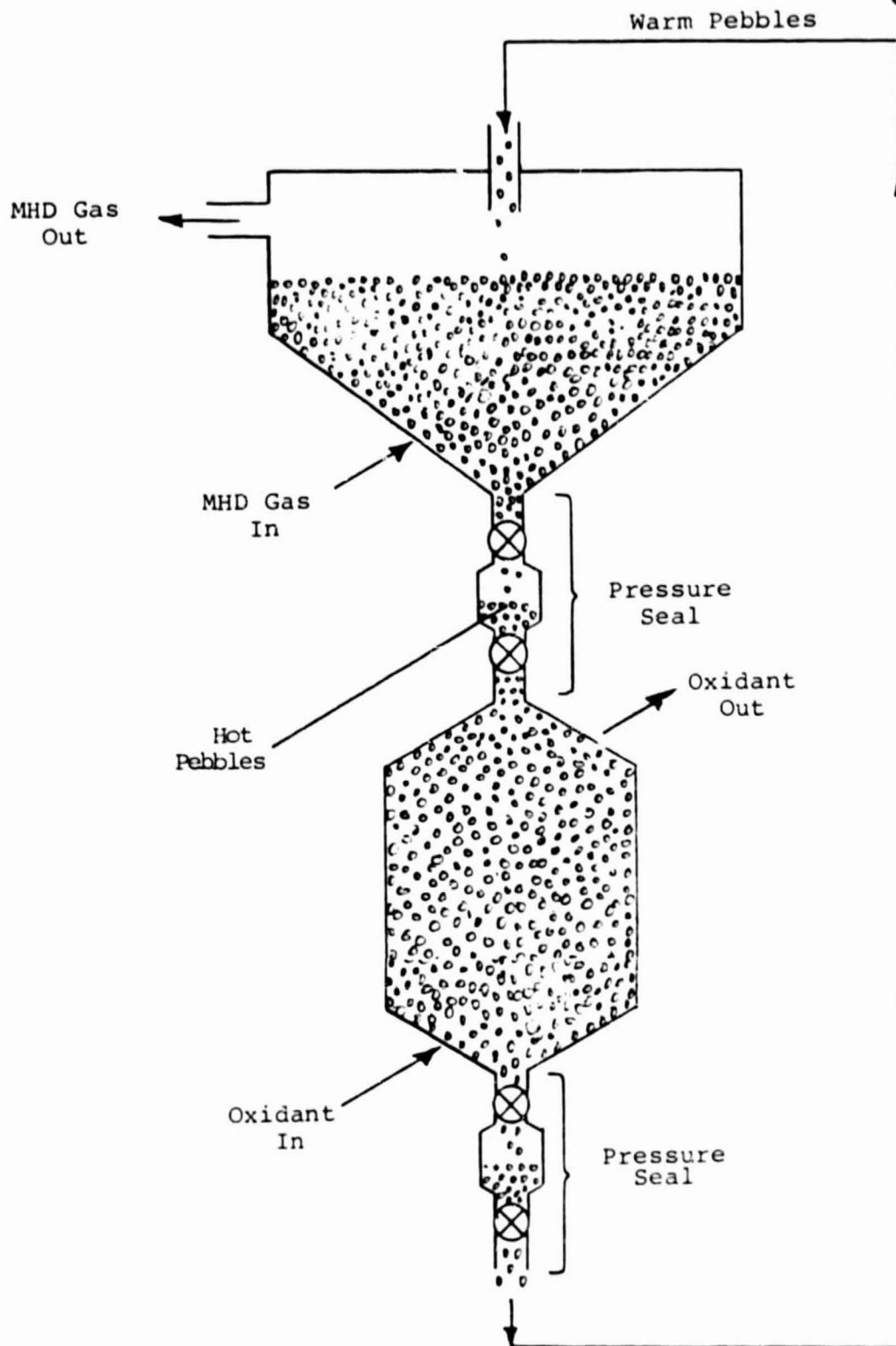


FIGURE 21. SCHEMATIC ARRANGEMENT OF MOVING PEBBLE  
BED CONCEPT FOR MHD INTERMEDIATE  
TEMPERATURE OXIDANT HEATER ARRANGEMENT

#### 4.2.3 Significant Design Considerations

Several significant design considerations in adapting the moving pebble bed concept to this application were considered. These considerations include:

- 1) the need to provide a pressure seal between the oxidant in the lower chamber and the MHD gas in the upper chamber;
- 2) the need to accommodate the large particulate loading of the MHD exhaust stream;
- 3) the need to minimize attrition of, and hence the need to replenish the supply of, the ceramic pebbles;
- 4) the need for uniform movement of the recirculating pebbles;
- 5) the need for uniform distribution of the MHD gas and oxidant through the pebble beds;
- 6) the need for a conveying system to transfer the pebbles from the lower chamber to the upper chamber; and
- 7) heater system heat losses and attendant insulation needs.

The most serious problem appears to be the pressure seal between the two chambers. In this application, a pressure difference of 5 atm must be maintained while continuously allowing the flow of ceramic pebbles at temperatures in excess of 1140 K (1600 F). The moving pebble heater applications discussed in Section 4.1 required balanced pressures in the two chambers in order to eliminate this problem.

Some pressure difference may be tolerated since the pebbles in the throat region between the chambers will act as a labyrinth seal. Information from Prof. Brzozowski indicated that a pressure difference of 290 Pa (.04 psi) could be tolerated in the Polish heater design. A calculation showed that an acceptably low leakage rate for the MHD application would be achievable with a throat sec-

tion having a length of 23 m (77 ft) with 25.4 mm (1 in) diameter pebbles. Throats with somewhat smaller lengths could be used if the diameter of the pebbles were decreased. Since a narrow throat of such a large length clearly would not be practical, merely relying on a labyrinth seal will not provide a practical solution to the pressure difference problem.

An arrangement which includes lock hoppers above and below the oxidant heating chamber is shown in Figure 21. It should be noted that the need to pressurize and depressurize the lock hoppers and the intermittent nature of the pebble flow resulting from their use will cause some departure from idealized continuous flow, resulting in flow, pressure, and temperature variations as in the fixed bed regenerator case. These variations would be expected to be smaller for the moving bed regenerator than for a fixed bed regenerator.

A pressure seal concept for a moving pebble bed heater was developed at the French Atomic Energy Commission by Dr. Yerouchalmi and colleagues. This concept is described in two French patents (Refs. 62 and 63) and illustrated in Figs. 22 and 23, which are extracted from the patents. It involves the use of pairs of refractory-faced disks, essentially constituting a high temperature double lock hopper arrangement, above and below the air heating pebble chamber. This concept was not applied to the Polish heater since there was no pressure difference between chambers. The concept could conceivably be developed for the MHD application. The inclusion of Figs. 22 and 23 is intended to illustrate that work has been done in this area and that at least one potential pressure seal concept exists.

A pressure seal utilizing rotary airlock or lock hopper concepts based on work in other areas could also conceivably be developed for the MHD application. Applications with similar needs to the moving pebble bed are coal conversion equipment and pressurized fluidized bed boilers (PFB). Lockhoppers are considered state-of-the-art equipment in coal conversion systems (Ref. 64), although the temperature levels experienced are not generally as high as for the moving pebble bed requirement.

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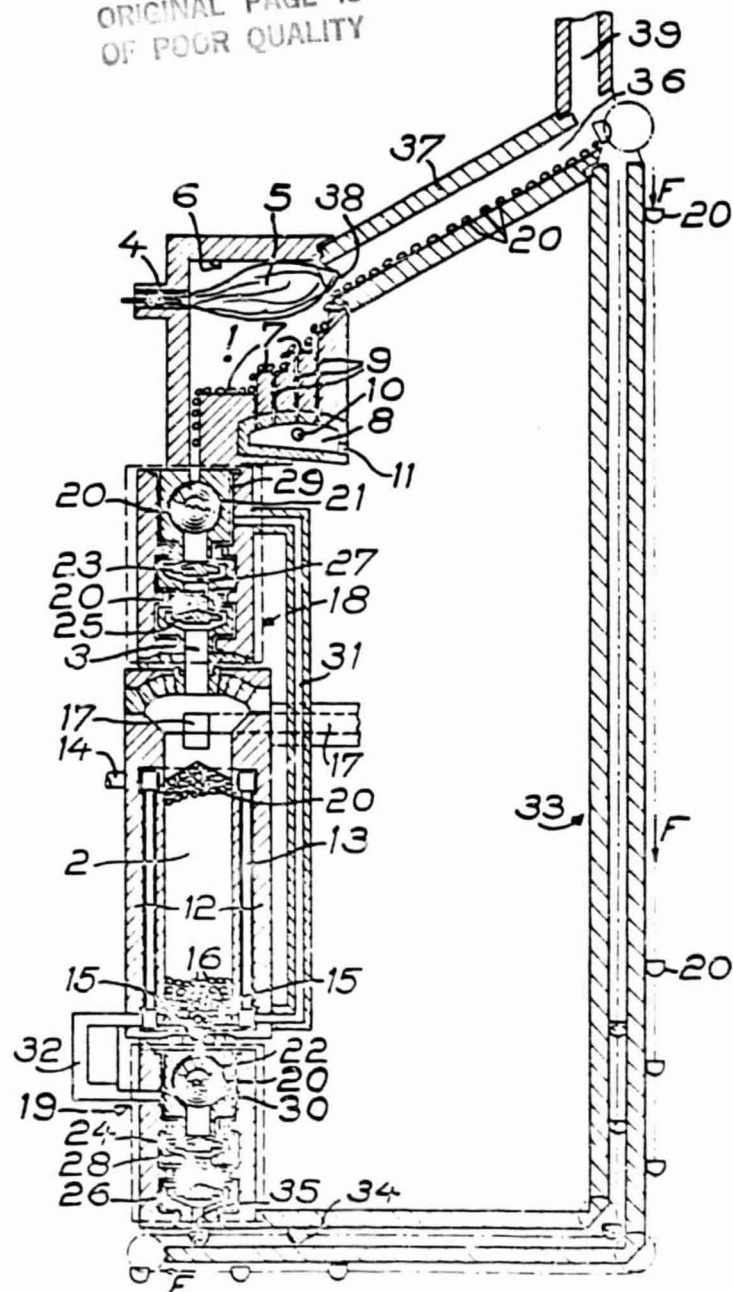


FIGURE 22. MOVING PEBBLE BED HEATER DESIGN  
WITH PRESSURE SEAL (From Reference  
63)

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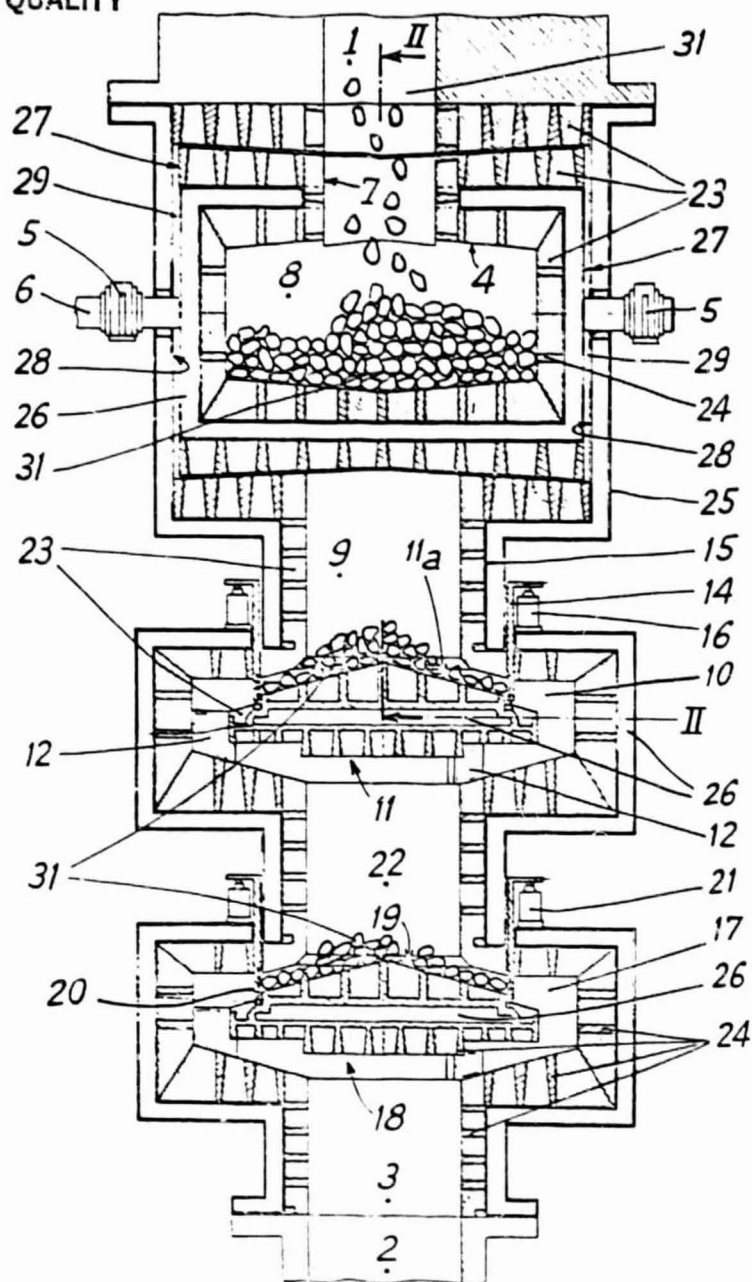


FIGURE 23. PRESSURE SEAL CONCEPT (From Reference 62)

Coal conversion equipment involves a number of requirements for transfer of solids into or out of a hot, high pressure region. An extensive program of development by DOE Morgantown Energy Technology Center (METC) is underway to meet these needs (Ref. 65).

One of several types of valves under development in this work is classified as Type III-discharge side, dry solids, 590 to 1370 K (600 to 2000 F). The desired pressure levels for valves of this type range from 0.24 to 11.1 MPa (20 to 1600 psig). Certain Type III valves would thus meet the needs of the moving pebble bed. Valves suitable for the moving pebble bed application are still under development in the DOE/METC program (Refs. 65, 66). Information from Ref. 66 indicates that the "state-of-the-art" of lockhopper valve service has increased from a life of 500 cycles at pressures up to 3.5 MPa (500 psig) and temperatures of about 590 K (600F) in 1976-1977 to a life of 15,000 cycles at 7.0 MPa (1000 psig) and 810 K (1000F) in 1980. Progress in this development program may result in making the lock hopper concept feasible for use as the pressure seal in a moving pebble bed heater. Increased temperature capability to roughly 1140 K (1600F) would be required.

Future developments in PFB technology may also provide useful concepts for the required pressure seal. In a pressurized fluidized bed combustor, ash must be removed from the combustor at conditions of about 1140 K (1600 F) and 10 atm. For some PFB pilot plant concepts, it is proposed that the ash be cooled before removal; while in other concepts, it is proposed that the ash be removed without pre-cooling.

The second major concern is fouling of the pebbles due to the particulate matter in the MHD gas stream. However, due to the abrasive action of the recirculating pebbles, the bed may tend to be self-cleaning. Some cleaning procedure may be required, however, before the pebbles are returned to the MHD gas chamber. A simple method of cleaning, such as passing the pebbles over a vibrating screen, as used with the recirculating granular bed in Ref. 54, would probably be sufficient.

The degree to which particles collect on the pebbles represents an advantage as well as a disadvantage, as discussed above. Particulate removal from the MHD

gas stream will result in a reduced particulate loading in downstream components; however, reentrainment in the lower chamber will tend to foul the oxidant stream. Since the particles are expected to be very small, as discussed in Section 2.1 most of the particles will likely pass through the upper chamber with the MHD gas stream. However, due to the meandering flow path and the small gaps between pebbles, some deposition is virtually certain to occur in this case, as opposed to the fixed bed regenerator and ceramic recuperator. Smaller pebble sizes will tend to increase the amount of particulate matter collected in the upper chamber.

With regard to pebble wear, a sufficient degree of abrasion resistance will be required in order to assure economical operation of the heater. Experience with the Polish heater using relatively inexpensive 96% alumina pebbles showed that replacement of approximately 25% of the pebbles would be required for each 6000 hours of continuous operation. For the heater size determined for this application, this would amount to replacement of roughly 111,000 kg/yr (245,000 lbm/yr) if the plant operates for 6000 hours, which is 68% availability in a year. The cost of this type of pebble is expected to be on the order of \$2-3/kg (\$1-1.5/lbm). An analysis of economic factors was not made as part of this engineering assessment. Such an analysis would be needed to make judgements as to the viability of the moving bed concept, and the above information will be useful for that purpose.

Promoting uniform movement of the solids and gases through the system represents a design consideration due to the anticipated shallow bed depths. These concerns are expected to require significant engineering effort if a practical design is to be developed.

The conveyor system also represents a design consideration. A pneumatic conveying system was initially used with the Polish heater. This system caused problems related to dust accumulation and fluctuations in the delivered air pressure and was replaced with a mechanical conveying system. The conveying system is not expected to cause major difficulties due to the extensive industrial experience with solids conveying, and a pneumatic system should not be ruled out. However, concern related to heat loss from the "warm" pebbles in the conveyor may require novel design features.



Heat losses from the heater system may be a concern due to the unusual shape of the heater system if a complex ducting system is required. To avoid attrition from the recirculating pebbles, insulation in the heater vessels will require an interior layer of material with sufficient abrasion resistance at the operating temperature. Insulating linings of relatively dense, abrasion resistant, 97% alumina have been used successfully in the Polish heater. The concept is to assure that the linings are more abrasion resistant than the pebbles, since replenishing the supply of pebbles is much less costly than replacing the vessel lining. Thus if highly abrasion resistant pebbles would be used, an even more abrasion resistant material would be required for the vessel linings. The internals of the pressure seal will also require abrasion resistant materials capable of withstanding the required temperature levels. Insulation backing the abrasion resistant linings should not present any unusual problems.

#### 4.3 Areas of Further Investigation

The pressure seal between chambers is critical in applying the moving bed heater to a MHD plant for oxidant preheat. Pressure seal concepts, especially those cited in this report, should be investigated to determine if a workable design is possible. If a workable design is possible, then further investigation of the degree of particulate collection expected to occur in the upper chamber and of methods for promotion of uniform solid and gas movement should be made. We feel that the other design considerations discussed in this report do not represent technical barriers to using the moving pebble heater.

An economic evaluation of the heater system should also be made to determine whether this type of heater would be economically viable.



## 5.0 HEATER SYSTEM MODIFICATIONS DUE TO LIQUID PARTICULATE MATTER IN MHD GAS STREAM

Qualitative changes that would be required for the three types of heater systems if liquid particulate matter were present in the MHD gas stream were considered. The major design considerations for this case and the resulting qualitative changes for each heater type are discussed in the following sections.

### 5.1 Design Considerations For Liquid Particulate Matter

If the temperature of the MHD gas at the inlet to the heater system were increased from 1294 K (1870 F) to 1367 K (2000 F), the heater requirements would be more severe due to the presence of liquid particulate matter. It is assumed that the liquid particulate matter would consist only of the potassium seed compounds, since Montana Rosebud Ash would be solid and dry at this temperature level. As discussed in Section 2.1, solid particles entering the heater system in the former case are expected to be very small. Similarly, it is expected that liquid particles in the latter case will be very small at the entrance to the heater system. However, as these liquid particles pass through the ducts and heat exchanger modules, some particles will deposit on duct walls and heat exchanger surfaces. This is a major difference from the dry, solid particulate case.

The major design considerations which arise in the liquid particulate case are: 1) the need for corrosion resistant materials, 2) deposition of the liquid particulate matter and solidification from the liquid phase on heat exchanger surfaces, and 3) the higher temperature level to which the heater materials would be exposed.

The first major design consideration is that liquid and vapor phase corrosion by potassium compounds are severe for most materials. Thus, the presence of liquid seed compounds (and the associated vapors) would require that corrosion resistant materials be used in each of the three heater types, at least in parts of the heater systems. Such materials would in all cases be more expensive than materials which can be used if only dry, solid particulate matter is present. As discussed above, however, at a temperature of 1367 K (2000 F) Montana Rosebud

ash would still be in a dry, solid state. Thus, corrosive conditions may not be as severe as would be the case at a somewhat higher temperature where the ash would also be in the liquid state.

The second major design consideration is that liquid particulate matter entering the heater system would solidify in the heater system itself as the temperature of the MHD gas stream is reduced. Solidification of liquid particles which remain entrained in the gas stream does not represent a concern. However, the large heat transfer surface area would promote deposition and subsequent agglomeration of the small particles into larger particles and eventually formation of a liquid film on the heater surfaces. This liquid would then solidify as the gas, liquid, and/or heat exchange surfaces move through the heat exchanger and the MHD gas temperature and the temperature of the deposits decrease. This would probably foul the heater and necessitate some form of periodic cleaning in order to operate the heater. The need to deal with this problem would also increase the cost of all three types of heater systems through such factors as increased heater flow passage size or spacings to accommodate some degree of deposition, addition of mechanical cleaning hardware, increased material temperature and/or strength requirements to accommodate thermal cleaning methods, or increased operating expenses due to the addition of fluxing or cleaning agents.

Again, it should be noted that the lack of liquid ash particles would make the 1367 K (2000 F) temperature case less severe than a higher temperature, in which case liquid ash particles would also solidify on heat exchanger surfaces. This is because potassium compounds which solidify from the liquid phase form a deposit which probably could be removed relatively easily by mechanical or thermal means in certain situations, whereas ash solidifies to a hard glassy deposit whose removal would be considerably more difficult.

The third major design consideration is that the increased temperature level would require the use of more insulation and possibly higher grade insulation (having greater service temperature limits or strength) in some locations, apart from the corrosion question. This would also increase the cost of the heater system, although the effect would be much smaller than the two previously mentioned considerations.

## 5.2 Qualitative Heater System Changes

The qualitative changes in each of the three heater types which would result from the presence of liquid particulate in the 1367 K (2000 F) MHD gas stream entering the heater system are discussed in the following. For each type of heater, consideration was given to materials selection, flow passage size or heat exchanger geometry, heater size, heater system cost, and operation and maintenance procedures.

### 5.2.1 Fixed Bed Regenerative Heater

The fixed bed heater conditions would be similar in some respects to those of the directly-fired high temperature air heater (HTAH) under development for advanced MHD plants (Refs. 67-70). Corrosion resistant materials similar to those proposed for the directly-fired HTAH would be suitable. The problem of deposition of seed/ash material in the heater flow passages would be easier to deal with due to fact that the ash material would be in a dry, solid form. However, the relatively low temperature of the MHD gas entering the heater system would require a somewhat different approach for cleaning the flow passages using thermal methods.

The concept presently envisioned for preventing deposits in the HTAH is to allow the entire heat storage matrix to reach a temperature greater than the seed melting point during each regenerative cycle, thus allowing deposits to flow from the matrix. Tests have demonstrated the ease of removal of potassium sulfate material from the HTAH using this method (Refs. 67,68). The HTAH will probably require the use of different materials in various vertical locations in the matrix in addition to this thermal cleaning technique. This is because different cored brick matrix materials appear to retain ash deposits to varying degrees when the ash solidifies from the liquid phase in the heater (Refs. 69,70). This requirement would not exist in the case of a 1367 K (2000 F) MHD gas inlet temperature.

Heating the entire heat storage matrix to a temperature essentially equal to the MHD gas temperature would not be feasible. Therefore, a somewhat different application of the thermal cleaning method would be required.

Two other thermal cleaning methods are suggested. With one method, an auxiliary combustor could be provided to periodically heat the individual heaters to a temperature sufficient to achieve the necessary deposit removal. This combustor would probably need to be fired by a clean fuel in order to avoid ash deposition. However, the necessary temperature level of the "cleanout" combustor could result in melting of the previously dry, solid ash particles thus creating conditions similar to those in a HTAH, and requiring similar removal methods. These methods are still under development, and once developed the use of the intermediate temperature heater may be less attractive than implementing a HTAH.

A second approach for removing or preventing buildup of deposits of seed material would be to introduce the MHD gas into the heaters from the bottom rather than the top, and introduce the oxidant from the top. This would result in an increasing thermal gradient, and thus decreasing seed material viscosity, in the downward direction, promoting ready drainage of seed material from the heaters. This approach would require development of a matrix support capable of withstanding temperatures up to almost 1367 K (2000 F). Concepts for such matrix supports are being studied and tested in the HTAH development work (Refs. 67-70). Again, once such a support concept has been developed, implementing the HTAH may be the most attractive approach. However, in this case, the lack of sticky ash particles may yet provide an advantage over the HTAH.

The various aspects involved in adapting the fixed bed regenerative type heater to the liquid particulate case using one or the other of the above methods are discussed in the following. Incorporation of a mechanical method for cleaning the heater system is also possible but was not considered in this study, since the thermal cleaning methods are felt to be more practical.

### Materials

Magnesia alumina spinel materials suitable for use in the lowest temperature regions of the HTAH have been shown in the HTAH development work to have good corrosion resistance in the MHD gas environment (Refs. 67-70). Fabrication of the checkers and matrix support components from spinel materials capable of being used at the relatively low, 1367 K (2000 F) service temperature would not pose a difficult problem. Spinel castable materials are available for use in the

duct and vessel linings. Thus material selection is not a barrier to the liquid particulate case, although the spinel material would be considerably more expensive than the material proposed for use in the dry, solid particulate case.

#### Flow Passage Size

The size of the flow passages could be increased to allow some build up of material between cleaning periods. This would probably dictate the use of a "standard" refractory checker rather than the "high efficiency" checker proposed in the conceptual design, which would increase the flow passage size by a factor of about 1.5. Using the MHD gas upflow method may prevent build up of deposits however, and thus allow use of similarly sized flow passages as in the dry, solid particulate case.

#### Heater Size

The requirement for a high temperature matrix support would probably limit the diameter of the individual heaters to a value less than proposed in the conceptual design, due to the more severe matrix support requirement. A smaller allowable heater size would necessarily increase the number of heaters in the system. For example, a matrix diameter limit of 4.3 m (14 ft) would result in an increase in the number of heaters from 4 to 14. The increased temperature would result in the insulation layers being somewhat thicker.

#### Heater System Cost

All of the design considerations for the liquid particulate case would result in increased costs for the heater system. The cost of the spinel materials would be expected to exceed the cost of the material proposed in the conceptual design by factors of about 6 for the checkers and matrix support and about 3 for the innermost castable layer. A larger number of heaters would require a larger number of smaller steel vessels, MHD gas and oxidant ducts, and flow sequencing valves. All things considered, an increase in the heater system cost by a factor of 2 or 3 would be expected.

## Operation and Maintenance

It was assumed in the conceptual design for the dry, solid particulate case that no special operating procedures would be required to prevent accumulation of deposits. For the liquid particulate case, operating procedures as discussed above would be required.

Maintenance needs would also be increased due to the presumably larger number of heaters and associated sequencing valves. Since the valve sizes would be somewhat smaller, the valves may be easier to fabricate and maintain. However, valve, duct and valve refractory lining and refractor checker service life would be shorter due to the more severe conditions.

### 5.2.2 Ceramic Recuperative Heater

Adapting the ceramic recuperative heater concept to the liquid particulate case would require replacement or protection of the silicon carbide proposed for use in the conceptual design since this material is highly susceptible to corrosion by liquid potassium compounds. Deposits would most likely form on the tubes, and provision for removal of these deposits would be required. The metallic flow baffle in the heat exchanger modules and the duct insulation materials would also require replacement or protection from the liquid potassium compounds. Several possible schemes for designing the ceramic recuperative heater to meet these objectives were considered.

The most direct approach would be to use seed-resistant materials for the heat exchanger tube and manifold assembly, the flow baffle, and the duct lining. Seed resistant castable materials exist which could be used for the flow baffle and duct linings. However, ceramic tube manufacturing and joining capabilities for materials other than silicon carbide are minimal, and even greater development efforts would be required than those required to produce the silicon carbide assembly proposed for the conceptual design. Also, the use of a castable flow baffle in the heat exchanger modules could inhibit the expansion capability of the tubular assembly and cause significantly greater stresses in the tubes.

Other concepts would maintain the silicon carbide tubes, but require protection of the silicon carbide from the liquid-particulate-bearing MHD gas. This pro-



tection could be provided by adding a radiant heat transfer section upstream of the tube bundle or by recirculating a portion of the MHD gas from downstream of the tube bundle to the upstream MHD gas. These methods would decrease the temperature at the inlet to the tubular section of the recuperator to the 1294 K (1870 F) level where the particulate would be dry and solid. In the case of recirculating the MHD gas flow, however, the oxidant outlet temperature could not be increased as much over the conceptual design level of 1144 K (1600 ) as in the case employing a radiant heat transfer section.

A radiant section could be constructed using silicon carbide tubes protected by a film of clean gas or by a protective tube or lining of seed-resistant material. It should be noted that the particulate matter may tend to agglomerate more and result in larger particles than would be the case if all of the gas cooling were performed in the upstream equipment due to the presumably different surface/volume ratio and cooling rate resulting from a number of smaller sections. This could require additional modifications to the heat exchanger modules proposed in the conceptual design.

The various considerations associated with these concepts for adapting the ceramic recuperator conceptual design to the liquid particulate case are discussed in the following paragraphs.

### Materials

As in the case of the fixed bed regenerative heater, magnesia alumina spinel materials would be the likely choice. Straight spinel tubes have been fabricated, but U-tubes and joining techniques have not been developed. The thermal conductivity and mechanical strength of spinel are also considerably lower than those of silicon carbide. This would require thicker tubes with associated higher thermal stresses, making tube failure more likely. A much larger mass of tube material would also be required.

One possibility would be to use straight spinel tubes to pass through the MHD gas and join these tubes to silicon carbide manifolds and U-tubes located external to the MHD gas stream. Since the thermal expansion coefficients for the two materials differ by roughly a factor of 2, however, this would require challenging joining technology development.

Spinel castables are available for use at the required service temperatures and could be used for the necessary duct liners.

#### Tube Spacing

If the liquid particulate were allowed to enter the tube bundle, i.e. if an upstream cooling section were not added, larger tube spacing than proposed in the conceptual design in Section 3.2 would be required to allow space for some buildup of deposits between periodic cleaning by mechanical or thermal means. Somewhat larger spacing than in the proposed conceptual design would probably be required even if an upstream section were included to cool the MHD gas. This is because the particles may tend to be larger in this case than if all cooling were done in the upstream equipment, as discussed previously. The required tube spacing would not be as large as if liquid particulate matter would be present in the tube bundle itself.

#### Heater Size

The heat exchanger modules would need to be larger to accommodate increased tube spacing or an upstream radiant or mixing section. Somewhat thicker insulation layers in the ducts and vessels would also be required due to the higher temperature level.

#### Heater System Cost

All of the factors considered would tend to increase the heater system cost. Estimation of the increase is difficult due to the uncertainty in cost of spinel tube assemblies and the various upstream MHD gas cooling possibilities, but an increase similar to that expected for the fixed bed heater (a factor of 2 or 3) would seem reasonable for adapting the ceramic recuperator conceptual design to the liquid particulate case.

#### Operation and Maintenance

Provision for sootblowers or some method of thermal cleaning, such as periodically heating the tubes by reducing the oxidant flow or by using an auxiliary



combustor, would be required if liquid particulate matter enters the tube bundle. If a radiant section were added to cool the MHD gas upstream of the tube bundle, provision for removal of at least some seed material in this section would be required. If recirculation of the MHD gas were used, the necessary valves, mixers, and controllers would also be required.

Due to the added complexity of the system, and the increased likelihood of ceramic tube failure if spinel tubes were used, maintenance requirements would be expected to increase.

### 5.2.3 Moving Bed Regenerative Heater

The meandering or labyrinth type flow path required of the MHD gas in this case will certainly result in accumulation of seed material on the moving pebbles. In view of the difficulty envisioned in promoting proper pebble movement even without the added complexity of accumulation of seed material, this additional factor poses a serious concern as to the technical feasibility of using a moving pebble bed heater in this case. However, the fact that all of the pebbles are physically removed from the heater vessels and are thus accessible for continuous cleaning may mitigate this concern and make the moving pebble bed viable in the liquid particulate case.

The various aspects involved in adapting the moving pebble bed heater to the liquid particulate case are discussed in the following.

#### Materials

Magnesia alumina spinel pebbles and spinel castable materials or bricks for duct liners, vessels and lock hopper valve linings, and other components of the heater system should be acceptable for use to prevent corrosion from potassium compounds. Sufficient strength and abrasion resistance should be achievable but the cost of these materials will be higher than materials which would be satisfactory in the absence of liquid particulate.



### Pebble Size

Larger sized pebbles would possibly be required to provide larger spaces between pebbles to allow for some accumulation of material.

### Heater Size

Since the size of individual heaters will probably be dictated by the distribution and flow requirements of the pebbles and gas, the presence of liquid particulate would probably not significantly affect the size of an individual heater. However, since the total volume of pebbles required will increase if the pebble size is increased, additional heater modules would probably be required.

### Heater System Cost

Since a conceptual design and cost estimate were not made for the moving pebble bed heater as part of this study, no estimate of additional cost for the liquid particulate case was made. The various factors, including different materials, additional heater modules, and pebble cleaning equipment, will tend to increase the cost of the heater system.

### Operation and Maintenance

Pebble cleaning will certainly be required in this case. Mechanical cleaning before transporting the pebbles into the MHD gas chamber would probably be required. Mechanical cleaning of the pebbles would be easier than mechanical cleaning of the fixed bed heater or the ceramic recuperator due to the accessibility of the pebbles. Periodic thermal cleaning of the pebbles with an auxiliary combustion system may also be feasible.

Maintenance needs would be increased due to the additional complexity and increased potential for fouling various components of the heater system.

## 6.0 TECHNICAL AND ECONOMIC COMPARISON OF ALTERNATIVES

### 6.1 Technology Status of Heater Concepts

Of the three heater types investigated, the conceptual design of the fixed-bed regenerative heater system is the closest to being based upon current technology. The ceramic-tube recuperative heater system conceptual design is based upon an extrapolation of current technology both in terms of system flow capacity and ceramic-tube manufacturing capabilities. The moving-bed regenerative heater system would require a development program since heaters of this type which meet the MHD system requirements have never been constructed, and several design features may require innovative approaches.

#### 6.1.1 Fixed Bed Regenerative Heater System

The fixed-bed regenerative type of heater design is derived from blast furnace stove technology and practice which is well established in the steel industry. The principles are well known and similar units have been built and operated. The dust-loading in the MHD application is more severe than in present commercial practice, but does not appear to present insurmountable problems. An extensive MHD high temperature air heater (HTAH) development program has been underway for several years. Many of the conditions for the HTAH testing apparatus have been much more severe than for the intermediate-temperature oxidant heater (ITOH) application and it has been demonstrated that solutions can be found to many of the features unique to the MHD application. The valves specified in the fixed bed regenerative heater system conceptual design are larger than those which are currently available commercially. This raises questions concerning the estimated costs of the valves and the confidence that such valves can be manufactured within a reasonable time frame. However, the system design can be modified to include a larger number of vessels requiring smaller valves.

#### 6.1.2 Ceramic - Tube Recuperative Heater System

Industrial processes presently exist which utilize ceramic-tube recuperative heaters (e.g. steel soaking pits) under conditions in which the pressure differential between the two heat-exchange fluids is minimal. The MHD ceramic-tube

recuperator conceptual designs are derived from concepts proposed under a program now underway to develop ceramic-tube recuperators under high differential-pressure conditions for such applications as gas turbines or coal gasification plants. To build such a heater system for the MHD ITOH application would require 1) a considerable increase in system dimensions and 2) the design and construction of manufacturing facilities to produce the ceramic tubing in much greater lengths than in presently available facilities. The technological considerations involved in doing this were not investigated. The economic feasibility of designing and constructing such manufacturing facilities also depends upon the existence of a sufficient market demand.

### 6.1.3 Moving Bed Regenerative Heater System

The use of the moving-bed regenerator concept has seen limited application in the chemical process industry. However, for these applications, there is no pressure differential between the two heat exchange fluids. Furthermore, there are no programs currently underway to develop a moving-bed regenerator which will operate with a large pressure differential. Due to limitations in the scope of this investigation, it was not possible to fully explore the technical feasibility of the moving bed regenerator concept. The necessity to provide a pressure seal was identified as the major design problem. Although no specific solution is identified, there are several technological areas (e.g. coal gasification and pressurized fluidized-bed combustion) in which similar problems arise. It is possible that the solution to the moving-bed regenerator pressure seal question can be derived from solutions developed for one of these other technologies. In summary, it is not clear to what extent the major technical problem areas for the moving-bed concept are amenable to solution.

## 6.2 Performance of Heater Systems

All three heater types (as conceptually proposed) meet the design requirements of delivering preheated oxidant at specified conditions of flow rate, pressure and temperature. However, only the ceramic-tube recuperator meets the specified conditions on a constant and continuous basis. The temperature of the preheated oxidant delivered by the fixed-bed regenerative heater system varies periodically, having a cycle time of approximately ten minutes. The delivered oxidant

pressure and flow rate are constant for portions of the cycle, but exhibit impulsive changes periodically. Thus the fixed-bed regenerative heater system is able to meet the design specifications only on a time averaged basis. Determination of the effect of the time-variations of the oxidant temperature on the performance of the other MHD plant components (combustor, MHD generator, etc.) was beyond the scope of this study. If it were to be determined that the magnitude of the temperature fluctuation associated with the conceptual design is excessive, design modifications would be required to reduce the magnitude of the fluctuations to an acceptable level.

Another facet of the periodic nature of the fixed-bed regenerator operation is that a small amount of mixing of the two fluid streams occurs when the flows to each of the vessels is switched from one fluid to the other. The result is that a small amount of MHD exhaust gas periodically enters the oxidant stream and a small amount of oxidant periodically enters the MHD gas stream. Continuous leakage of oxidant through the valves into the MHD exhaust gas stream also occurs at a small rate. Such flow-stream mixing is taken into account in the conceptual design of the fixed bed regenerative heater system. However, the effect which the mixing has on the other MHD plant components has not been determined.

The moving bed regenerative heater system was only investigated to a limited extent and the deviations in preheated oxidant conditions with respect to time were not determined. Several of the potential methods of providing a pressure seal (e.g. lock hoppers) may introduce periodic disruptions in the continuous output of preheated oxidant. However, the magnitudes and cycle times of such disruptions were not determined. The possibility of particulate matter carryover from the MHD gas to the oxidant stream would likely occur to a greater extent for the moving bed heater than for the other two types of heaters, but the magnitude of such carryover and the effect it would have on the MHD plant performance and operation were not determined.

The heat loss for the fixed-bed regenerative system was estimated to be 4.8% of the heat duty while that of the ceramic-tube recuperator system was estimated to be 6.4%. Both of these values are considered to be within acceptable limits. Tradeoff studies of heat loss versus system cost were not made because of the

limited scope of the study. Such optimization would have only a minor effect on total system cost.

### 6.3 Reliability and Maintenance of Heater Systems

#### 6.3.1 Fixed Bed Regenerative Heater System

The components of the fixed-bed regenerative heater system which are most likely to fail or to require maintenance are the sequencing valves. If the failure or maintenance requirements of a valve is extensive, it may be preferable to replace the existing valve with a spare to minimize the shutdown period. This would require the acquisition of spare valves, which is an additional expense. Special provisions for valve replacement are required (e.g., hoists) since the valves are very large. Fluidyne has estimated a 10 to 15 year lifetime for the sequencing valves and 15 to 20 years for refractory checkers and vessel and duct linings. Therefore, each valve will require replacement (with a new or refurbished valve) every 10 to 15 years and replacement of the refractory matrix in the vessels and refractory insulation in the vessels and ducting is expected to be required every 15 to 20 years. Replacement of valves and refractory materials can be performed during scheduled plant outages.

In accordance with the original design specifications, the conceptual design of the fixed-bed heater is based upon the utilization of all of the vessels in the system in order to meet design requirements. If a single vessel must be temporarily taken out of service for maintenance (e.g. for refractory replacement or repair), the remaining vessels can still be utilized and the power plant can be operated at part-load capacity until the plant is shut down for service. If this is deemed to be an unacceptable condition, the design specification could be modified to require the system to be designed so that the full required pre-heat capacity can be temporarily provided by the remaining vessels when one of the vessels is taken out of service.

#### 6.3.2 Ceramic - Tube Recuperative Heater System

The ceramic-tube recuperative heater system conceptual design requires that all of the heater modules be in operation in order to meet design conditions. That



is, there are no spare modules and there is no excess capacity incorporated into the system. Furthermore, there is no provision for isolating any of the modules to enable a module or a bank of modules to be taken out of service for repair work without having to shut down the plant. Due to the limited scope of this investigation, no assessment has been made of the possible types of heater failures, their probabilities of occurrence and effects of such failures. It is presumed that the system can continue to operate if there are minor tube failures. However, if such an assessment were to reveal that the overall plant availability is severely compromised by the present conceptual design, it would be necessary to modify the design to include spare modules or extra heat exchange capacity and a means for isolating modules or banks of modules. The isolation would be required for both the MHD gas side and the oxidant side of the modules. Although the lifetime of the refractory insulation has been estimated to be 15 to 20 years, no assessment has been made of the expected lifetime of the ceramic tubing.

#### 6.3.3 Moving Bed Regenerative Heater System

The moving bed regenerative heater system has not been investigated in sufficient detail to identify the major reliability/maintenance factors. The pebbles are expected to undergo attrition so that provision must be made for periodic replacement of pebbles which no longer meet specifications. Reliability and maintenance considerations will be important factors in the selection of the pressure seal mechanism and the pebble recirculation scheme.

#### 6.4 Effects of Liquid Particulate Matter

In the qualitative investigation of the design modifications required for operation at higher MHD gas temperatures (where liquid particulate matter would be present), corrosion, fouling and clogging due to the formulation of deposits were identified as the major effects of liquid particles. The extent and nature of the corrosion and fouling would depend upon the MHD gas temperature range. Below the ash fusion temperature, the particulate matter can consist of liquid seed and dry ash particles. Above the ash fusion temperature, the ash particles can be sticky or liquified and the seed can be in the form of liquid particles (or vapors, above the dew points of the seed compounds).

For the two types of heater system for which the conceptual designs have been prepared, it has been ascertained that the capital cost of the systems would be substantially increased under conditions of liquid particulate matter. Furthermore, the uncertainty in the technology status of each of the concepts would also increase. To determine whether the additional cost of the equipment would be justified, it would be necessary to conduct a cost-benefit analysis which includes the increase in plant efficiency associated with the increase of the oxidant preheat temperature. Such an analysis would require a quantitative assessment of the effects of liquid particulate matter over a wide MHD gas temperature range.

Because of the preliminary nature of the engineering assessment of the moving-bed regenerative heater concept, the effects of liquid particulate matter were difficult to determine. One feature of this type of heater may make the moving bed concept less susceptible to corrosion, fouling and clogging than the two other heater types. This feature is that the necessity to recirculate the pebbles offers an opportunity to transport the pebbles to a device in which the deposited particulate matter can be removed more easily than it can be removed from the surfaces in the matrix of the fixed-bed system or the tubing of the recuperative system. Further investigations would be required to validate this assertion.

#### 6.5 Cost Estimates

The estimated costs for the fixed bed regenerative heater system and the ceramic-tube recuperative heater system are shown side-by-side in Table XIV. The total cost for the two heater systems are \$19,298,000 and \$15,824,000, respectively. These costs estimates do not include contingencies or the costs of transporting equipment and materials from the manufacturing plants to the MHD power plant site. They also do not include the costs of spare parts or materials. Table XV shows estimated transportation costs per 100 lb. for various distances. In an overall economic assessment, the expenditures for replacement of valves and refractory materials over the life of the plant should be considered as part of the maintenance cost.



TABLE XIV. SUMMARY OF COST ESTIMATES FOR FIXED-BED REGENERATIVE AND CERAMIC TUBE RECUPERATIVE HEATER SYSTEMS

Component Description	Fixed Bed Heater Cost Estimate * (\$1000's)	Recuperative Heater Cost Estimate * (\$1000's)
Heater Vessels (Modules)		
Steel	1525	274
Refractory Insulation (installed)	596	294
Checker Matrix (installed)	2939	N.A.
Matrix Support (installed)	1552	N.A.
Ceramic Header/Tube Assembly	<u>N.A.</u>	<u>7460</u>
Total Vessels (Modules)	6612	8028
MHD Gas and Oxidant Ducting (with installed insulation)	2283	3803
Sequencing Valves	6548	N.A.
Major Expansion Joints and Miscellaneous Parts	462	348
Support Structure and Foundations	1639	600
Controls and Instrumentation	877	-
Erection and Assembly (excluding refractory installation but including silicon carbide header/tube installation)	877	3045
TOTAL HEATER SYSTEM	<u>19298</u>	<u>15824</u>

\* The cost estimates in this table do not include costs of transportation from manufacturing plant to power plant site and do not include contingency costs. See Section 6.5 of text and Table XV for further discussion and information.

TABLE XV. APPROXIMATE TRANSPORTATION COSTS PER  
45.4 KG (100 LBM) OF MATERIAL

Distance (miles)	Freight Rate* per 45.4 kg (100 lbm) (dollars)
100	2.51
200	3.24
300	3.96
400	4.58
500	5.05
600	5.64
800	6.72
1000	7.56
1200	8.53
1400	9.37
1600	10.20
1800	11.08
2000	12.01

\* Based upon Rail transportation with minimum shipment of 10,900 kg (24,000 lbm).

The cost estimate for the fixed bed regenerative heater system is considered to be a "budgetary" cost estimate. In accordance with American Association of Cost Engineers (AACE) guidelines, the cost estimate is thus considered to be accurate to within plus 30 percent and minus 15 percent. The cost estimate for the ceramic tube recuperative heater system is considered to be an "order-of-magnitude" cost estimate and is thus considered to be accurate to within plus 50 percent and minus 30 percent, in accordance with AACE guidelines.

The conclusions which can be drawn from the cost estimates fall into two categories: (a) comparison of the costs of the two types of heater system with each other and (b) comparison of the costs of ceramic intermediate-temperature oxidant heater systems with alternatives such as the metallic "low-temperature" oxidant heater system. With regard to the first category, the ceramic-tube recuperator cost estimate is lower than the fixed-bed regenerator cost estimate by approximately 18 percent. Although this difference is significant, it must be qualified by two factors. First, the cost estimate for the ceramic-tube recuperator is based upon a conceptual design which includes no spare modules or isolation valves and is therefore of uncertain system reliability. Secondly, the cost estimate for the recuperative heater is much more uncertain than that of the regenerative heater because of the differences in the technology status of the two heater types. The contingency costs which would be added to the costs presented in Table XIV should reflect this difference in technology status.

For the second category of comparisons (b, above), it is necessary to account for the capital cost of the metallic low-temperature oxidant heater as well as the difference in power plant efficiency associated with increasing the oxidant preheat temperature from the 1200°F limit imposed by metallic heaters to the 1600°F range allowed by the use of ceramic heaters. Thus a comparison of the cost of electricity would be required to determine whether an expense of 19 million dollars for a heater system based on a nearly current fixed-bed heater technology or 16 million dollars for a heater system based on a more advanced ceramic-tube recuperator technology would be justified relative to the cost of the metallic low temperature oxidant heater system.

## 7.0 CONCLUSIONS

Conceptual designs and cost estimates were developed for the fixed bed regenerative and ceramic recuperative type heaters. An installed cost of \$19,298,000 in 1980 dollars was estimated for the fixed bed regenerative heater system. It is felt that the design and construction of this system could be accomplished with presently available industrial materials and technology.

An installed cost of \$15,824,000 in 1980 dollars was estimated for the ceramic recuperative type heater. There is a much greater uncertainty in this estimate due to the uncertain cost of the tubular ceramic components. In contrast to the fixed bed regenerator, considerable development as well as expanded manufacturing capabilities would be required in order to produce the ceramic components necessary for the recuperative heater.

The pressure seal between chambers was identified as the most critical component for the moving bed regenerative type heater as a result of the engineering assessment which was made. Investigation of the degree of particulate collection by the moving medium and of methods for promoting uniform solid and gas movement were also identified as important design considerations bearing on the technical feasibility of this concept. An economic evaluation of the moving bed heater should be made.

Significant changes would be required in all three types of heaters if they were to be exposed to liquid particulate matter in the MHD gas stream. This is due to 1) the need for corrosion resistant materials and 2) concerns related to deposition of the seed material and solidification from the liquid phase on heat exchanger surfaces. The costs of all three types of heaters would be greater in this case.

## 8.0 Recommendations for Further Investigations

There are several areas of possible further investigation. These areas can be subdivided into three categories: (a) assessment of the implications of the results obtained in the present investigation; (b) pursuit of some of the questions raised in the present investigation and (c) validation of assumptions which have been identified as being somewhat uncertain in the present investigation.

In category (a), an overall system evaluation and economic assessment of an MHD power plant should be conducted to determine the benefits achievable from utilizing a ceramic intermediate-temperature oxidant heater system to achieve higher preheat temperatures as compared to a metallic "low-temperature" oxidant preheater, as discussed above in section 6.5. Another investigation, which is required in conjunction with the fixed-bed regenerative heater system, is the effect of temperature ripple on the performance of other plant components (e.g., combustion, MHD generator) and, hence, on the overall plant performance, as discussed in section 6.2. This latter question must be considered in terms of a dynamic system performance analysis.

Under category (b) there are a large number of areas which can be recommended, including that of preparing a conceptual design and cost estimate of the moving bed regenerative heater system, since it appears to be technically feasible from an overall viewpoint. Particular attention should be given to the pressure seal, since that appears to be the component of greatest uncertainty.

The conceptual design of the ceramic-tube recuperative heater is based upon an approach proposed by AiResearch (Refs. 45-48) which is only one of several possible schemes. Other schemes, such as those proposed by Rocketdyne (Ref. 41) and Hague International (Refs. 38-40), may also be found to be suitable for this application and should be given further consideration.

As stated previously, the conceptual designs do not represent optimized systems. Additional conceptual design work would be required and should include consideration of alternate configurations and parametric analyses to determine the optimum conditions for operation. Although the prime incentive for conducting

such additional work would be the possibility of cost reductions, further investigations may also reveal that reliability and availability considerations would lead to the requirement of additional equipment (e.g., isolation valves for the ceramic-tube recuperative heater system) or more costly components (e.g., thicker ceramic tubing).

Since the cost of replacement of valves, refractory materials, ceramic tubing and ceramic pebbles over the life of the MHD plant may represent a significant cost, further substantiation of the estimates of the lifetimes of these items should be made. Such estimates can be made on the basis of experience in the utilization of such items in other industries such as the steel industry.

Under category (c), there are several possible investigations in which additional data can be developed to provide support for the assumptions made in the study or to indicate where adjustments in the assumptions may have to be made. One of these areas is that of determination of the temperature of the MHD gas at which the particulate matter in the gas becomes solidified. An accurate determination of this temperature would require an extensive experimental testing program which would encompass the wide range of variations in the conditions which would affect this temperature. However, further work can also be done through the use of mathematical modeling techniques incorporating experimental data which presently exist.

Another area in this category is that of the techniques and facilities for manufacturing the ceramic tubing for recuperative heater system. The uncertainty regarding the fabrication of the ceramic tubing is the main source of uncertainty in both the technology status and the cost estimate for this type of heater.

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APPENDIX A

SPECIFICATIONS FOR MHD OXIDANT INTERMEDIATE  
TEMPERATURE CERAMIC HEATER SYSTEMS

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## APPENDIX A

### SPECIFICATIONS FOR MHD OXIDANT INTERMEDIATE TEMPERATURE CERAMIC HEATER SYSTEMS

#### A.1 Definitions of Heater Systems

##### A.1.1 Fixed Bed, Periodic Flow, Ceramic Brick Regenerative Heater System

This type of heater system consists of a number of insulated metallic heat exchanger shells containing ceramic bed materials which are alternately heated by MHD exhaust gases and cooled by compressed oxidant which is utilized in the MHD combustor. The system also includes ducting, insulation, valving, flanges, expansion joints, structural supports, foundations and directly related auxiliary equipment. Interconnecting ducting to other components, such as compressors, is not included.

##### A.1.2 Ceramic Tube and Shell Recuperative Heater System

This type of heater system is a stationary, continuous flow ceramic tube and shell heat exchanger in which heat from the MHD exhaust gas is transferred to the enriched air via the ceramic tubes. The system also includes headers, insulation, structural supports, foundations and directly related auxiliary equipment. Interconnecting ducting to other components, such as compressors and combustors, is not included.

##### A.1.3 Moving Bed, Continuous Flow, Ceramic Bead Regenerative Heater System

This type of heater system consists of two chambers (or sets of chambers) containing ceramic pebbles which are heated by MHD generator exhaust gases in one chamber (or set of chambers) and pass to the other chamber (or set of chambers) where they heat the compressed oxidant which is utilized in the MHD combustor. The system also includes ducting, insulation, valving, pressure seals, pebble conveyors, flanges, expansion joints, structural supports, foundations and directly related auxiliary equipment. Interconnecting ducting to other components, such as compressors and combustors, is not included.

## A.2 Definition of Open-Cycle MHD Power Plant Conditions

### A.2.1 Power Plant Configuration and Size

The MHD power plant utilizes oxygen enriched air which is preheated in the intermediate temperature oxidant heater system by exhaust gases from the MHD generator as indicated in Figure A-1. The heat flow conditions specified below are for a nominal power plant output of 490 Mwe, with 235 Mwe produced by the MHD generator and 255 Mwe produced by the steam bottoming plant.

### A.2.2 Type of Coal and Seed

The fuel for the MHD power plant is Montana Rosebud coal dried to five (5) percent moisture. The combustion gas is seeded with a mixture of 68 percent  $K_2SO_4$  and 32 percent  $K_2CO_3$ .

### A.2.3 Oxidant Stream Flow Conditions

The oxidant stream properties are presented in Table A-I. The flow conditions are as follows:

Flow Rate (kg/sec)	230
Inlet Temperature ( $^{\circ}F$ )	460
Exit Temperature ( $^{\circ}F$ )	1600
Exit Pressure (atm)	6
Composition (mole % $O_2$ )	28

### A2.4 MHD Gas Stream Flow Conditions

The MHD gas stream composition and properties are presented in Tables A-II and A-III. The flow conditions are as follows:

Flow Rate (kg/sec)	330
Inlet Temperature ( $^{\circ}F$ )	1870
Exit Pressure (atm)	1

All particulate matter in the MHD gas stream is in solid form.



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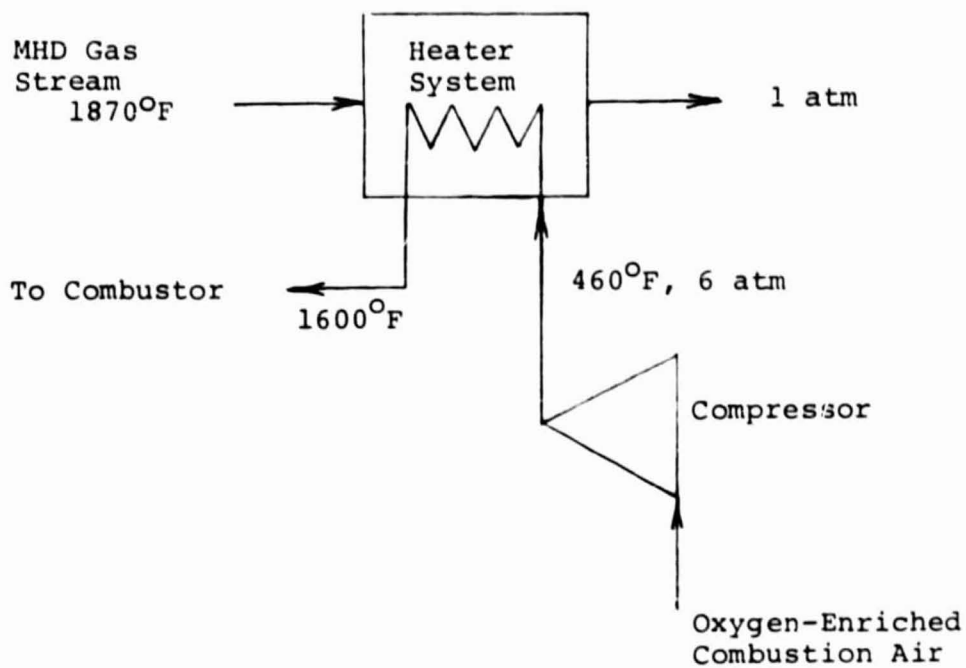


Figure A-1 Intermediate Temperature Oxidant Heater System Configuration.

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TABLE A-I

PROPERTIES OF OXYGEN ENRICHED AIR

MOLE PERCENT OXYGEN = 28.000 PERCENT OXYGEN ENRICHMENT = 32.74 MOLECULAR WT = 29.1493

GAS CONSTANT = 1.6491314 BTU/(LB)(R)

TEMPERATURE DEG F	ENTHALPY BTU/LB	RELATIVE PRESSURE	ENTROPY AT 1 ATM	CP BTU/(LB)(R)	GAMMA	RELATIVE VOLUME	INTERNAL ENERGY, BTU/LB
32.	-45.54	2.2407	1.62513	0.2309	1.3975	219.4230	-79.0644
60.	-38.84	2.7209	1.63542	0.2390	1.3971	190.9955	-74.2515
77.	-34.78	3.0453	1.64612	0.2392	1.3983	176.1993	-71.3773
-40.	-62.73	1.2370	1.58737	0.2333	1.3977	326.0579	-91.3433
-20.	-57.95	1.5147	1.59349	0.2333	1.3993	290.2324	-87.7366
-0.	-53.18	1.7702	1.60911	0.2333	1.3997	257.6682	-84.5249
20.	-48.40	2.0550	1.61923	0.2333	1.3996	233.4200	-81.1125
40.	-43.63	2.3711	1.62904	0.2339	1.3994	210.7330	-77.6937
60.	-38.85	2.7207	1.63342	0.2390	1.3991	191.0071	-74.2529
80.	-34.06	3.1059	1.64745	0.2392	1.3983	173.7545	-70.8645
100.	-29.28	3.5293	1.65616	0.2394	1.3984	158.5915	-67.4427
120.	-24.49	3.9921	1.66456	0.2396	1.3979	145.2036	-64.0172
140.	-19.70	4.4975	1.67269	0.2393	1.3974	133.3333	-60.5873
160.	-14.90	5.0479	1.68057	0.2401	1.3963	122.7530	-57.1525
180.	-10.08	5.6455	1.68820	0.2404	1.3961	113.3055	-53.7122
200.	-5.24	6.2930	1.69560	0.2407	1.3954	104.8251	-50.2600
220.	-0.44	6.9931	1.70279	0.2410	1.3946	97.1909	-46.8133
240.	4.36	7.7485	1.70979	0.2414	1.3933	90.2974	-43.3537
260.	9.19	8.5613	1.71659	0.2417	1.3929	84.0562	-39.8887
280.	14.03	9.4363	1.72323	0.2421	1.3920	78.3353	-36.4120
300.	18.87	10.3747	1.72969	0.2425	1.3911	73.2233	-32.9290
320.	23.73	11.3636	1.73600	0.2430	1.3901	68.5030	-29.4376
340.	28.59	12.4563	1.74216	0.2434	1.3891	64.1977	-25.9371
360.	33.47	13.6061	1.74813	0.2439	1.3881	60.2423	-22.4274
380.	38.35	14.8325	1.75407	0.2444	1.3870	56.6100	-18.9080
400.	43.24	16.1395	1.75992	0.2449	1.3859	53.2644	-15.3705
420.	48.15	17.5309	1.76566	0.2454	1.3847	50.1781	-11.8392
440.	53.06	19.0105	1.77099	0.2460	1.3836	47.3249	-8.3037
460.	57.99	20.5809	1.77640	0.2465	1.3824	44.6834	-4.7277
480.	62.92	22.2475	1.78171	0.2471	1.3812	42.2369	-1.1556
500.	67.87	24.0135	1.78692	0.2476	1.3800	39.9637	2.4273
520.	72.83	25.8837	1.79203	0.2482	1.3788	37.8403	6.0223
540.	77.80	27.8625	1.79706	0.2488	1.3775	35.8756	9.6274
560.	82.78	29.9529	1.80199	0.2494	1.3763	34.0424	13.2481
580.	87.78	32.1612	1.80684	0.2500	1.3750	32.3267	16.8783
600.	92.78	34.4913	1.81161	0.2507	1.3737	30.7223	20.5213
620.	97.80	36.9491	1.81631	0.2513	1.3725	29.2224	24.1772
640.	102.83	39.5325	1.82092	0.2519	1.3712	27.8126	27.8452
660.	107.85	42.2435	1.82547	0.2525	1.3699	26.4925	31.5253
680.	112.93	45.1309	1.82995	0.2532	1.3686	25.2525	35.2192
700.	118.00	48.1451	1.83435	0.2533	1.3673	24.0867	38.9254
720.	123.09	51.3351	1.83870	0.2545	1.3661	22.9857	42.6445
740.	128.13	54.6413	1.84299	0.2551	1.3648	21.9553	46.3766
760.	133.29	58.1317	1.84721	0.2553	1.3635	20.9911	50.1210
780.	138.41	61.7950	1.85137	0.2564	1.3623	20.0810	53.8801
800.	143.55	65.6340	1.85543	0.2571	1.3610	19.1923	57.6514
820.	148.70	69.6542	1.85954	0.2577	1.3598	18.3717	61.4353
840.	153.86	73.8653	1.86354	0.2584	1.3585	17.5951	65.2333

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TABLE A-1 (Cont'd)

PROPERTIES OF OXYGEN ENRICHED AIR

MOLE PERCENT OXYGEN = 23.000 PERCENT OXYGEN ENRICHMENT = 32.74 MOLECULAR WT = 29.14353

GAS CONSTANT = 1.2251914 BTU/(LB)(R)

TEMPERATURE DEG F	ENTHALPY BTU/LB	RELATIVE PRESSURE	ENTROPY AT 1 ATM	CP BTU/(LB)(R)	GAMMA	RELATIVE VOLUME	INTERNAL ENERGY, BTU/LB
860.	159.03	73.2701	1.25749	0.2590	1.3573	15.3504	59.0437
880.	164.22	82.3794	1.27139	0.2597	1.3561	16.1640	72.8575
900.	169.42	87.8972	1.27525	0.2593	1.3549	15.5241	76.7042
920.	174.64	92.7313	1.27905	0.2590	1.3537	14.3731	80.5513
940.	179.86	97.9026	1.28281	0.2586	1.3525	14.2540	84.4163
960.	185.10	103.4777	1.28653	0.2583	1.3513	13.7195	88.2917
980.	190.35	109.2042	1.29020	0.2579	1.3502	13.1333	92.1793
1000.	195.62	115.1075	1.29384	0.2575	1.3491	12.6723	96.0805
1020.	200.89	121.4066	1.29743	0.2572	1.3480	12.1377	99.9933
1040.	206.18	127.3759	1.30093	0.2568	1.3469	11.7255	103.9195
1060.	211.49	134.6533	1.30449	0.2564	1.3458	11.2357	107.8576
1080.	216.80	141.8985	1.30799	0.2560	1.3447	10.8659	111.8075
1100.	222.13	149.0107	1.31140	0.2556	1.3437	10.4962	115.7701
1120.	227.46	156.6474	1.31480	0.2552	1.3427	10.0347	119.7443
1140.	232.81	164.5515	1.31817	0.2548	1.3417	9.7203	123.7301
1160.	238.17	172.7937	1.32150	0.2543	1.3407	9.3731	127.7276
1180.	243.55	181.3570	1.32479	0.2539	1.3397	9.0411	131.7364
1200.	248.93	190.2491	1.32806	0.2535	1.3388	8.7216	135.7564
1220.	254.33	199.4055	1.33129	0.2530	1.3379	8.4200	139.7875
1240.	259.73	209.0825	1.33449	0.2525	1.3370	8.1299	143.8292
1260.	265.15	219.0255	1.33766	0.2521	1.3361	7.8522	147.8816
1280.	270.57	229.3162	1.34079	0.2516	1.3353	7.5853	151.9443
1300.	276.01	240.0051	1.34390	0.2512	1.3344	7.3313	156.0175
1320.	281.46	251.0372	1.34698	0.2508	1.3336	7.0878	160.1001
1340.	286.91	262.5713	1.35003	0.2503	1.3329	6.8540	164.1926
1360.	292.35	274.4635	1.35305	0.2500	1.3321	6.6279	168.2943
1380.	297.83	286.7722	1.35604	0.2497	1.3314	6.4151	172.4049
1400.	303.34	299.5139	1.35900	0.2494	1.3307	6.2039	176.5243
1420.	308.83	312.6929	1.36194	0.2490	1.3300	6.0112	180.6522
1440.	314.33	326.3413	1.36485	0.2487	1.3293	5.8211	184.7891
1460.	319.84	340.4414	1.36774	0.2483	1.3287	5.6383	188.9342
1480.	325.36	355.0200	1.37060	0.2480	1.3280	5.4635	193.0879
1500.	330.83	370.0930	1.37343	0.2476	1.3274	5.2951	197.2500
1520.	336.42	385.6531	1.37624	0.2473	1.3267	5.1333	201.4204
1540.	341.95	401.7322	1.37903	0.2470	1.3261	4.9775	205.5983
1560.	347.51	418.3413	1.38179	0.2467	1.3254	4.8278	209.7857
1580.	353.07	435.4344	1.38453	0.2463	1.3248	4.6837	213.9804
1600.	358.63	453.1777	1.38724	0.2460	1.3242	4.5449	218.1830
1620.	364.21	471.4243	1.38994	0.2457	1.3236	4.4114	222.3936
1640.	369.79	490.2712	1.39261	0.2453	1.3230	4.2827	226.6120
1660.	375.38	509.6926	1.39526	0.2450	1.3224	4.1587	230.8382
1680.	380.93	529.7114	1.39789	0.2447	1.3218	4.0393	235.0723
1700.	386.53	550.3494	1.40049	0.2443	1.3213	3.9240	239.3136
1720.	392.20	571.6567	1.40303	0.2440	1.3207	3.8129	243.5626
1740.	397.82	593.5259	1.40556	0.2437	1.3201	3.7057	247.8192
1760.	403.44	616.1559	1.40807	0.2434	1.3196	3.6024	252.0823
1780.	409.08	639.4466	1.41057	0.2431	1.3190	3.5027	256.3542
1800.	414.72	663.3862	1.41303	0.2428	1.3185	3.4063	260.6323

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TABLE A-1 (Cont'd)

PROPERTIES OF OXYGEN ENRICHED AIR

MOLE PERCENT OXYGEN = 23.000 PERCENT OXYGEN ENRICHMENT = 32.74 MOLECULAR WT = 29.14355

GAS CONSTANT = 0.0681916 BTU/(LB)(R)

TEMPERATURE DEG F	ENTHALPY BTU/LB	RELATIVE PRESSURE	ENERGY AT 1 ATM	CF BTU/(LB)(R)	GAMMA	RELATIVE VOLUME	INTERNAL ENERGY, BTU/LB
1620.	420.37	663.0571	2.01572	0.2326	1.3130	3.3132	264.9150
1640.	426.03	713.4155	2.01319	0.2330	1.3175	3.2234	269.2104
1660.	431.69	739.5530	2.02264	0.2333	1.3169	3.1366	273.5100
1680.	437.35	765.4249	2.02213	0.2337	1.3164	3.0527	277.8162
1700.	443.04	794.0567	2.02549	0.2340	1.3159	2.9716	282.1296
1720.	448.72	822.4914	2.02757	0.2344	1.3154	2.8932	286.4500
1740.	454.41	851.7159	2.03327	0.2347	1.3149	2.8175	290.7769
1760.	460.11	881.7725	2.03254	0.2350	1.3145	2.7441	295.1103
1780.	465.82	912.5637	2.03493	0.2354	1.3140	2.6731	299.4514
1800.	471.53	944.4170	2.03732	0.2357	1.3135	2.6044	303.7979
1820.	477.24	977.0166	2.03363	0.2360	1.3130	2.5380	308.1509
1840.	482.97	1010.5053	2.04193	0.2363	1.3126	2.4737	312.5105
1860.	488.70	1044.9121	2.04421	0.2367	1.3121	2.4114	316.8767
1880.	494.43	1030.2546	2.04646	0.2370	1.3117	2.3510	321.2495
1900.	500.15	1116.5542	2.04373	0.2373	1.3112	2.2925	325.6234
1920.	505.92	1153.7742	2.05097	0.2376	1.3105	2.2358	330.0127
1940.	511.68	1191.9522	2.05319	0.2379	1.3104	2.1810	334.4041
1960.	517.44	1231.2251	2.05540	0.2382	1.3100	2.1277	338.8010
1980.	523.21	1271.4146	2.05759	0.2385	1.3095	2.0762	343.2041
2000.	528.98	1312.7143	2.05977	0.2388	1.3091	2.0261	347.6123
2220.	534.76	1355.0464	2.06193	0.2391	1.3087	1.9775	352.0253
2240.	540.54	1395.4363	2.06409	0.2394	1.3083	1.9304	356.4432
2260.	546.33	1443.0117	2.06622	0.2397	1.3079	1.8847	360.8745
2280.	552.13	1488.6529	2.06835	0.2399	1.3075	1.8404	365.3062
2300.	557.93	1535.4219	2.07046	0.2402	1.3071	1.7973	369.7441
2320.	563.74	1583.4121	2.07255	0.2405	1.3068	1.7555	374.1873
2340.	569.55	1632.4541	2.07463	0.2408	1.3064	1.7150	378.6365
2360.	575.37	1682.7337	2.07671	0.2410	1.3060	1.6756	383.0901
2380.	581.19	1734.3740	2.07876	0.2413	1.3056	1.6373	387.5493
2400.	587.02	1787.1643	2.08081	0.2416	1.3053	1.6001	392.0149
2420.	592.85	1841.2103	2.08284	0.2418	1.3049	1.5639	396.4849
2440.	598.69	1896.6259	2.08486	0.2421	1.3046	1.5287	400.9604
2460.	604.54	1953.3442	2.08687	0.2424	1.3042	1.4947	405.4409
2480.	610.39	2011.3257	2.08887	0.2426	1.3039	1.4615	409.9272
2500.	616.24	2070.5864	2.09085	0.2429	1.3035	1.4292	414.4185
2520.	622.10	2131.1520	2.09283	0.2431	1.3032	1.3979	418.9148
2540.	627.97	2193.0506	2.09479	0.2434	1.3028	1.3673	423.4155
2560.	633.84	2257.4294	2.09674	0.2436	1.3025	1.3377	427.9207
2580.	639.71	2323.5525	2.09868	0.2439	1.3022	1.3088	432.4314
2600.	645.59	2389.2330	2.10061	0.2441	1.3019	1.2804	436.9475
2620.	651.47	2457.3556	2.10252	0.2443	1.3015	1.2533	441.4675
2640.	657.35	2526.9257	2.10443	0.2446	1.3012	1.2267	445.9932
2660.	663.26	2598.2055	2.10633	0.2448	1.3009	1.2007	450.5205
2680.	669.15	2671.3053	2.10821	0.2450	1.3006	1.1755	455.0544
2700.	675.06	2745.1331	2.11008	0.2453	1.3003	1.1509	459.5959
2720.	680.97	2821.4460	2.11193	0.2455	1.3000	1.1270	464.1354
2740.	686.83	2899.1731	2.11376	0.2457	1.2997	1.1036	468.6875
2760.	692.79	2978.6770	2.11564	0.2459	1.2994	1.0809	473.2402

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OF POOR QUALITY

TABLE A-1 (Cont'd)

PROPERTIES OF OXYGEN ENRICHED AIR

MOLE PERCENT OXYGEN = 28.000 PERCENT OXYGEN ENRICHMENT = 32.74 MOLECULAR WT = 27.1455

GAS CONSTANT = 0.0481914 BTU/(LB)(°R)

TEMPERATURE DEG F	ENTHALPY BTU/LB	RELATIVE PRESSURE	ENTROPY AT 1 ATM	CP BTU/(LB)(°R)	GAMMA	RELATIVE VOLUME	INTERNAL ENERGY, BTU/LB
2760.	698.71	3059.8315	2.11743	0.2962	1.2971	1.0533	477.7774
2800.	704.64	3142.7933	2.11730	0.2964	1.2939	1.0372	482.3584
2820.	710.57	3227.5555	2.12112	0.2964	1.2926	1.0162	485.9243
2840.	716.50	3313.8309	2.12292	0.2963	1.2933	0.9957	491.4741
2860.	722.44	3402.2229	2.12471	0.2970	1.2930	0.9757	496.0479
2880.	728.38	3492.4341	2.12650	0.2972	1.2977	0.9562	500.6467
2900.	734.33	3584.5711	2.12827	0.2974	1.2975	0.9373	505.2283
2920.	740.28	3678.6242	2.13004	0.2975	1.2972	0.9187	509.8159
2940.	746.23	3774.7189	2.13180	0.2973	1.2970	0.9006	514.4067
2960.	752.19	3872.6157	2.13354	0.2980	1.2967	0.8830	519.0007
2980.	758.16	3972.6235	2.13525	0.2982	1.2964	0.8653	523.5996
3000.	764.12	4074.6319	2.13701	0.2984	1.2962	0.8481	528.2021
3020.	770.09	4178.3247	2.13873	0.2986	1.2959	0.8327	532.8083
3040.	776.07	4285.0273	2.14044	0.2988	1.2957	0.8167	537.4192
3060.	782.04	4393.4727	2.14215	0.2990	1.2954	0.8011	542.0359
3080.	788.03	4504.0469	2.14386	0.2992	1.2952	0.7859	546.6516
3100.	794.01	4616.7734	2.14553	0.2994	1.2950	0.7710	551.2739
3120.	800.00	4731.7333	2.14720	0.2996	1.2947	0.7565	555.8994
3140.	805.99	4849.0547	2.14888	0.2997	1.2945	0.7423	560.5263
3160.	811.99	4968.6800	2.15054	0.2999	1.2943	0.7285	565.1619
3180.	817.99	5090.4573	2.15219	0.3001	1.2940	0.7150	569.7976
3200.	824.00	5214.3320	2.15383	0.3003	1.2938	0.7013	574.4377
3220.	830.00	5341.5733	2.15547	0.3005	1.2936	0.6889	579.0815
3240.	836.01	5470.7555	2.15710	0.3006	1.2934	0.6763	583.7283
3260.	842.03	5602.3567	2.15872	0.3008	1.2932	0.6639	588.3789
3280.	848.05	5736.4683	2.16034	0.3010	1.2929	0.6519	593.0327
3300.	854.07	5873.2227	2.16194	0.3011	1.2927	0.6401	597.6902
3320.	860.09	6012.5039	2.16354	0.3013	1.2925	0.6286	602.3513

MASS FRACTIONS O2 0.30746 N2 0.67487 AR 0.01151 CO2 0.00041 H2O 0.00575  
MOLE FRACTIONS O2 0.25000 N2 0.70203 AR 0.00340 CO2 0.00027 H2O 0.00930

COMPOSITION OF STREAM MIXED WITH AIR TO ATTAIN ABOVE MIXTURES

MASS FRACTIONS O2 1.00000 N2 0.00000 AR 0.00000 CO2 0.00000 H2O 0.00000  
MOLE FRACTIONS O2 1.00000 N2 0.00000 AR 0.00000 CO2 0.00000 H2O 0.00000

TABLE A-II

THERMODYNAMIC EQUILIBRIUM PROPERTIES AT ASSIGNED  
273°K to 2500°K TEMPERATURE AND PRESSURE at 1 atm.

CASE NO.	200									MOLES	ENERGY CAL/MOL	STATE	TEMP DEG K	DENSITY G/CC
		CHEMICAL FORMULA												
FUEL	C	5.61422	H	4.44310	M	0.07301	S	0.03431	O	0.91846	1.000000	-41251.593	S	298.15
FUEL	SI	1.00000	O	2.00000							0.025500	-217697.000	S	298.15
FUEL	AL	2.00000	O	3.00000							0.007100	-420497.250	S	298.15
FUEL	H	2.00000	O	1.00000							0.292100	-62317.375	L	298.15
FUEL	H	2.00000									17.759	6271.614	G	1144.40
FUEL	O	2.00000									6.625779	6515.661	G	1144.40
FUEL	AN	1.00000									0.212100	4201.054	G	1144.40
FUEL	C	1.00000	O	2.00000							0.305900	-26167.163	G	1144.40
FUEL	H	2.00000	O	1.00000							0.235500	-53110.109	G	1144.40
FUEL	K	2.00000	C	1.00000	O	3.00000					0.026000	-274165.910	S	298.15
FUEL	K	2.00000	S	1.00000	O	4.00000					0.091700	-343522.250	S	298.15
O/F = 0.0000		PERCENT FUEL = 100.0000				EQUIVALENCE RATIO = 0.9509				PHI = 0.0000				REACTION DENSITY = 0.0000

## THERMODYNAMIC PROPERTIES

P, ATM	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
T, DEG K	2500.0	2400.0	2300.0	2200.0	2100.0	2000.0	1900.0	1800.0	1700.0	1600.0	1500.0	1400.0	1300.0	1200.0
PHO, G/CC	1.4625-4	1.5445-4	1.6231-4	1.7053-4	1.7924-4	1.8850-4	1.9875-4	2.0997-4	2.2264-4	2.3692-4	2.5355-4	2.7291-4	2.9593-4	3.2393-4
M, CAL/G	-53.542	-125.37	-192.37	-246.57	-293.49	-334.94	-372.73	-406.61	-445.65	-493.20	-531.71	-565.57	-597.93	-629.33
U, CAL/G	-216.54	-255.17	-301.57	-353.59	-402.60	-448.35	-491.58	-532.95	-574.42	-619.95	-662.64	-703.82	-743.93	-783.52
G, CAL/G	-5554.83	-5441.91	-5221.91	-5004.44	-4789.30	-4576.23	-4365.14	-4155.98	-3953.33	-3744.18	-3542.27	-3342.70	-3143.12	-2943.12
S, CAL/(G)(K)	2.2445	2.2140	2.1863	2.1627	2.1409	2.1206	2.1013	2.0819	2.0607	2.0319	2.0070	1.9840	1.9620	1.9400
M, MOL WT	39.127	30.416	30.432	30.754	30.836	30.949	30.956	31.012	31.057	31.249	31.331	31.351	31.354	31.354
CDLV/MPST	-1.00000	-1.00000	-1.00000	-1.00000	-1.00000	-1.00000	-1.00000	-1.00000	-1.00000	-1.00000	-1.00000	-1.00000	-1.00000	-1.00000
CDLV/MPST	1.2472	1.2021	1.1360	1.0591	1.0547	1.0310	1.0174	1.0170	1.0364	1.0713	1.0191	1.0330	1.0330	1.0330
CP, CAL/(G)(K)	0.7653	0.6957	0.5553	0.5024	0.4529	0.4031	0.3544	0.3554	0.3550	0.4315	0.3510	0.3320	0.3110	0.2890
GTTA (S)	1.1411	1.1443	1.1599	1.1751	1.1919	1.2054	1.2218	1.2250	1.2163	1.1993	1.2253	1.2444	1.2553	1.2653
SON VEL./SEC	637.3	657.2	650.9	635.6	620.9	605.8	589.2	579.1	563.4	546.5	529.7	513.4	497.3	481.3

## MOLE FRACTIONS

ALDZ-	0.00001	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
ALDZM	0.00000	0.00001	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
ALDZ(S)	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
ALDZ(L)	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
AP	0.00764	0.00771	0.00776	0.00780	0.00782	0.00784	0.00785	0.00786	0.00787	0.00789	0.00791	0.00791	0.00791	0.00791
CO	0.01132	0.02476	0.01567	0.00910	0.00679	0.00527	0.00406	0.00317	0.00242	0.00182	0.00134	0.00091	0.00053	0.00020
CO2	0.14635	0.17973	0.17021	0.15779	0.14276	0.12573	0.10723	0.08765	0.06740	0.04641	0.02573	0.01523	0.00923	0.00523
E	0.00000	0.00001	0.00001	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
H	0.00141	0.00074	0.00036	0.00016	0.00007	0.00002	0.00001	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
H2	0.00315	0.00215	0.00140	0.00084	0.00047	0.00024	0.00011	0.00005	0.00002	0.00001	0.00000	0.00000	0.00000	0.00000
H2O	0.00157	0.00176	0.00194	0.00215	0.00235	0.00254	0.00270	0.00285	0.00297	0.00307	0.00315	0.00322	0.00328	0.00333
K	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
K2	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
K2O	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
K2SO4(S)	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000

TABLE A-II (cont'd)

K2SO4(L)	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
K2SO4	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
H2O	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
H2	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
O	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
F4	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
O2	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
SO2	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
SO3	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
SO	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
SiO2(S)	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
SiO2(L)	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
SiO2	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000

ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN 0.50000E-05 FOR ALL ASSIGNED CONDITIONS

C2H6	C2H6	AL(S)	AL(L)	AL	AL	ALH	ALH(S)	ALH	ALO
ALC+	ALC+	ALOH	ALOH	ALOH-	ALC+	ALC	ALC	ALC+	ALC+
ALC2O+	ALC2O+	C(S)	C	C+	C-	CH	CH	CH2	CH2O
CH3	CH4	CH	CH+	CH-	CHH	CH2	CH2	CH2-	C5
C52	C2	C2-	C2H	C2H2	C2H	C2H2	C2H	C3	C5O2
C6	C5	H+	H-	HALO	HCH	HCO	HCO+	HCO	H2O
H2O2	H2O3	H2O	H2O(S)	H2O(L)	H2O2	H2S	H2SO4(L)	H2SO4	K(S)
K(L)	KOH(S)	KOH(L)	KOH	KH	KO-	KOH(S)	KOH(S)	KOH(L)	KOH+
K2O(S)	K2	K2CO3(S)	K2CO3(L)	K2CO3H2	K2O(S)	K2O2(S)	K2O2H2	K2S(S)	K2S(S)
K2S(S)	K2S(L)	K2SO4(S)	H	H+	H-	HCO	H2	H2	H2S
H2+	H2	H2-	H2O3	H2H4	H2O	H2O+	H2O4	H2O5	H3
O+	-	OH+	OH-	OS	S(S)	S(L)	S	S+	SH
S4	S2	S2O	S2	Si(S)	Si(L)	Si	Si+	SiC	SiC2
Si4	Si4	SiH4	SiH	SiO2(S)	SiO2(S)	SiS	Si2	Si2C	Si2H
Si3	Si3H4(S)								

Tables A - II and A - III indicate properties, at chemical equilibrium, for the combustion of Montana Rosebud coal dried to 5%, with 80% slag rejection of the combustor, and 5% excess oxygen to account for completion of combustion in the radiant furnace. A seed mixture of 68% by weight of potassium sulfate ( $K_2SO_4$ ) and 32% potassium carbonate ( $K_2CO_3$ ) is injected at the combustor which results in 70%  $SO_2$  removal to meet the 1979 NSPS for Montana Rosebud coal. In producing the tables, no allowance was made for ash condensation and removal in the radiant furnace.



THERMODYNAMIC EQUILIBRIUM PROPERTIES AT ASSIGNED  
273°K to 2500°K TEMPERATURE AND PRESSURE at 1 atm

CASE NO.	209										MOLES	ENERGY CAL/MOL	STATE	TEMP - DEG K	DENSITY G/CC
CHEMICAL FORMULA															
FUEL	C	5.61420	H	4.44510	M	0.07301	S	0.03431	O	0.91246	1.000000	-61251.593	S	293.15	0.0000
FUEL	SC	1.00000	O	2.00000							0.025500	-217699.000	S	293.15	0.0000
FUEL	AL	2.00000	O	3.00000							0.007100	-400499.000	S	293.15	0.0000
FUEL	H	2.00000	O	1.00000							0.022100	-68317.375	L	293.15	0.0000
FUEL	H	2.00000									17.729	8271.416	G	1144.40	0.0000
FUEL	O	2.00000									6.022797	6030.461	G	1144.40	0.0000
FUEL	AR	1.00000									0.010000	4200.094	G	1144.40	0.0000
FUEL	C	1.00000	O	2.00000							0.001900	-24167.103	G	1144.40	0.0000
FUEL	H	2.00000	O	1.00000							0.035500	-56130.309	G	1144.40	0.0000
FUEL	K	2.00000	C	1.00000	O	3.00000					0.004000	-27505.913	S	293.15	0.0000
FUEL	K	2.00000	S	1.00000	O	4.00000					0.011700	-34302.509	S	293.15	0.0000
O/F = 0.0000      PERCENT FUEL = 100.0000      EQUIVALENCE RATIO = 0.9509      PHI = 0.0000      REACTANT DENSITY = 0.0000															

## THERMODYNAMIC PROPERTIES

P. AYM	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
T. DCG K	1200.0	1100.0	1000.0	900.0	800.0	700.0	600.0	500.0	400.0	300.0	200.0	100.0	0.0
RHO. G/GC	3.1843E-4	3.4738E-4	3.6212E-4	4.2460E-4	4.7771E-4	5.4593E-4	6.3768E-4	7.4465E-4	9.3553E-4	1.3714E-3	1.3531E-3	1.4525E-3	1.5525E-3
H. CAL/G	-629.03	-639.41	-659.69	-719.19	-768.35	-808.83	-850.33	-892.05	-934.63	-978.07	-982.47	-912.97	-720.72
U. CAL/G	-765.65	-739.33	-693.06	-776.22	-779.06	-720.53	-641.84	-552.05	-451.27	-322.59	-223.55	-92.94	-916.32
G. CAL/G	-2753.75	-2756.62	-2569.71	-2382.79	-2197.64	-2020.67	-1844.63	-1673.60	-1507.55	-1345.95	-1184.03	-1032.47	-880.75
S. CAL/G(G)K	1.9366	1.9222	1.9195	1.9454	1.9141	1.7766	1.7344	1.6860	1.6299	1.4310	1.4763	1.4500	1.4253
H. MOD MT	31.354	31.355	31.355	31.357	31.359	31.361	31.366	31.372	31.372	31.376	33.826	34.364	34.759
COLV.IMPPT	-1.00000	-1.00001	-1.00001	-1.00002	-1.00002	-1.00002	-1.00010	-1.00001	-1.00000	-1.01578	-1.03195	-1.01700	-1.00521
COLV.IMPJP	1.00001	1.00001	1.00003	1.00004	1.00005	1.00006	1.00018	1.00002	1.00000	1.03064	1.05674	1.02601	1.01193
CP. CAL/G(G)K	0.20064	0.20353	0.20779	0.21920	0.22854	0.23743	0.24704	0.24651	0.22513	0.21192	0.25794	0.31171	0.42753
G. CAL/G	1.2537	1.2543	1.2706	1.2776	1.2508	1.2769	1.3073	1.3221	1.3370	1.1553	1.1575	1.1762	1.2264
SON VEL/CM/SEC	622.9	607.3	580.4	550.2	522.2	490.6	456.0	418.6	376.5	292.2	291.0	256.5	203.3

### POLE FRACTIONS

[illegible]



TABLE A-II (Cont'd)

SIZE(S) 0.0001 0.0005 0.001 0.002 0.005 0.01 0.02 0.05 0.1 0.2 0.5 1.0 2.0 5.0 10.0

ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN 0.00000001 FOR ALL ASSIGNED CONDITIONS

C2H6	C2H4	AL(S)	AL(L)	AL	AL+	ALH	ALN(S)	ALH	ALO
AL0+	AL0-	ALOH	ALOH+	ALOH-	AL02	AL02-	AL02H	AL0	AL20
AL20+	AL202	AL202+	AL202(L)	AL+	C(S)	C	C+	C-	CH
CH+	CH2	CH20	CH3	CH4	CH	CH+	CH-	CHH	CH2
CO	CO2	CO2-	CS	CS2	C2	C2-	C2H	C2H2	C2H
C2H2	C2D	C3	C302	C4	C5	E	H	H+	H-
H2O	H2H	HCO	HCO+	HHC0	HHC0	HHC02	HHC03	H2	H2
H2O(S)	H2O2	H2S	K(S)	K(L)	K	K+	KH(S)	KH(L)	KCH
PH	PO	KO-	KOH	KOH(S)	KOH(L)	KOH(S)	KOH(L)	K2	K2
K2CO3(S)	K2CO3(L)	K2C2H2	K2O(S)	K2O2(S)	K2O2H2	K2S(S)	K2S(S)	K2S(L)	K2S(L)
K2SO4(L)	K2SO4	H	H+	H-	HCO	HHC0	HHC02	HHC03	H2O+
H2	H22-	H2S	H2H4	H2O	H2O+	H2O4	H2O5	H3	O
C+	O+	OH	OH+	OH-	OS	S(S)	S(L)	S	S+
S+	S-	SO	S2	S20	S8	S1(S)	S1(L)	SI	SI+
S10	S102	SIH	SIH+	SIH4	SIH	S10	S102(L)	S102	S15
S12	S120	S12H	S13	S13H4(S)					

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THERMODYNAMIC EQUILIBRIUM PROPERTIES AT ASSIGNED  
1300°K to 1400°K TEMPERATURE AND PRESSURE at 1 atm

CASE NO.	201							MOLES	ENERGY CAL/MOL	STATE	TEMP DEG K	DENSITY G/CC			
CHEMICAL FORMULA															
FUEL	C	5.44510	H	4.44510	M	0.07301	S	0.03431	O	0.91646	1.000000	-41251.593	S	292.15	0.0000
FUEL	ST	1.00000	O	2.00000							0.025560	-217699.000	S	292.15	0.0000
FUEL	AL	2.00000	O	3.00000							0.007160	-400699.250	S	292.15	0.0000
FUEL	H	2.00000	O	1.00000							0.272100	-60317.375	L	292.15	0.0000
FUEL	H	2.00000									17.789	6271.414	G	1164.40	0.0000
FUEL	O	2.00000									6.506799	6532.461	G	1164.40	0.0000
FUEL	AR	1.00000									0.210000	4204.094	G	1164.40	0.0000
FUEL	C	1.00000	O	2.00000							0.006900	-84167.100	G	1164.40	0.0000
FUEL	H	2.00000	O	1.00000							0.235000	-50150.299	G	1164.40	0.0000
FUEL	K	2.00000	C	1.00000	O	3.00000					0.026000	-274595.935	S	292.15	0.0000
FUEL	K	2.00000	S	1.00000		4.00000					0.091700	-343022.500	S	292.15	0.0000

O/F# 0.0000 PERCENT FUEL= 100.0000 EQUIVALENCE RATIO= 0.9509 PHIL= 0.0000 REACTANT DENSITY= 0.0000

## THERMODYNAMIC PROPERTIES

P. ATM	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
T. DSG K	1450.0	1390.0	1380.0	1370.0	1360.0	1350.0	1340.0	1330.0	1320.0	1310.0	1300.0
RAC, G/C	2.72727-4	2.74535-4	2.74537-4	2.75030-4	2.75033-4	2.75333-4	2.75135-4	2.72727-4	2.74947-4	2.91666-4	2.91933-4
H. CALG	-555.50	-555.50	-571.49	-574.67	-577.26	-581.03	-585.32	-585.32	-591.64	-594.77	-597.93
U. CALG	-655.52	-655.50	-655.95	-661.52	-664.65	-668.60	-670.25	-672.72	-675.30	-677.81	-680.32
G. CALG	-3362.72	-3322.29	-3303.73	-3283.30	-3263.54	-3243.81	-3224.10	-3204.42	-3184.74	-3165.13	-3145.52
S. CALG(G)(K)	1.9648	1.9617	1.9794	1.9771	1.9745	1.9724	1.9692	1.9669	1.9645	1.9621	1.9597
H. FOLG	31.351	31.352	31.352	31.353	31.353	31.353	31.353	31.353	31.354	31.354	31.354
DELTA DELT	-1.00012	-1.00010	-1.00005	-1.00006	-1.00005	-1.00004	-1.00003	-1.00003	-1.00002	-1.00002	-1.00001
DELTA DELT	1.00012	1.00025	1.0021	1.0017	1.0014	1.0011	1.0009	1.0008	1.0006	1.0005	1.0004
CP, CALG(G)(K)	0.3220	0.3226	0.3194	0.3133	0.3174	0.3165	0.3164	0.3163	0.3151	0.3144	0.3135
C/TTA (S)	1.2545	1.2573	1.2567	1.2594	1.2593	1.2510	1.2503	1.2515	1.2521	1.2526	1.2533
CON VEL, G/SEC	662.4	672.2	676.0	673.8	671.5	669.2	666.7	664.4	662.0	659.7	657.7

### MOLE FRACTIONS

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TABLE A-III (Cont'd)

ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN  $0.50000E-03$  FOR ALL ASSIGNED CONDITIONS

CZHS	CZHA	AL(S)	AL(L)	AL	AL*	ALH	ALN(S)	ALM	ALQ
ALC*	ALO-	ALOH	ALOH*	ALOII-	ALOZ	ALOZ-	ALOZH	ALS	ALZQ
ALZQ*	ALZQZ	ALZQZ*	ALZQZ(L)	AR*	C(S)	C	C*	C-	CH
CH*	CH2	CH2*	CH2(L)	CH4	CH	CH*	CH-	CHN	CH2
CO	CO*	CO2	CO2	CS2	CZ	CZ-	CZH	CZH2	CZH
CZ*	CZ*	CZ*	CZ*	C*	C*	E	H	H*	H*
H2O	H2O	H2O	H2O	H2O	H2O	H2O2	H2O2	H2O2	H2
H2O(S)	H2O(L)	H2O2	H2O2(L)	H2SO4(L)	H2SO4	K(S)	K(L)	K	K*
H2O2(S)	H2O2(L)	KOH	KOH(L)	K2O	K2O(S)	KOH(S)	KOH(S)	KOH(L)	KOH*
H2O2(L)	K2	K2CO3(S)	K2CO3(L)	K2C2H2	K2O2(S)	K2O2(S)	K2O2H2	K2S(S)	K2S(S)
H2O2(S)	K2S(L)	H2SO4(S)	H	H*	H-	H2O	H2O	H2O2	H2
H2O*	H2O2	H2O2-	H2O3	H2H4	H2O	H2O*	H2O4	H2O5	H3
O	O*	O-	OH*	OH-	O3	S(S)	S(L)	S	S*
SH	SH	SO	S2	S2O	S3	S(S)	S(L)	S1	S1*
SIC	SIC2	SIH	SIH*	SIH4	SIH	S10	S102(S)	S102(S)	S102(L)
S1Q2	S1S	S1Z	S1ZC	S1ZH	S1Z	S1ZH4(S)			

In Table A III, the temperature increments have been decreased to provide greater detail in the temperature regime of 1300° K to 1400° K where potassium sulfate ( $K_2SO_4$ ) solidifies.

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APPENDIX B

TEMPERATURE RANGE FOR SOLID STATE OF  
PARTICULATE MATTER IN AN MHD GAS STREAM

TEMPERATURE RANGE FOR SOLID STATE OF  
PARTICULATE MATTER IN MHD EXHAUST GAS STREAMObjective

The primary objective of the MHD oxidant intermediate temperature ceramic heater study is to compare and assess three potential ceramic heater approaches for preheating an MHD power plant oxidant to 1600°F by MHD exhaust gas. The temperature range is higher than allowable for metallic heaters and lower than the fusion temperature of particulate matter in the MHD stream. To design the heaters, it is first necessary to establish the temperature range in which the entrained particulate matter of a coal-fired MHD exhaust-gas stream would be solid. The establishment of this parameter is the objective of this phase of the study.

The particulate matter originates from ash constituents in the coal and from the potassium seed injected into the combustor. The plasma is produced by burning Montana Rosebud coal with air enriched with oxygen to a level of 28 mole percent and seeded with a mixture of potassium carbonate and potassium sulfate.

Introduction

Investigation of the solidification (freezing) temperature range of ash and seed components covered the following aspects:

1. Determination of chemical constituents present in the MHD exhaust gas in the temperature range of 1600 to 2000°F.
2. Determination of phase-change temperatures of each constituent.
3. Determination of particle size distribution.
4. Determination of the temperature vs. time history of the particles with the lowest melting points.

5. Evaluation of the results of steps 1 through 4 to determine the MHD exhaust gas temperature for which particles are solidified.
6. Consideration of engineering aspects related to the application of the results from step 5, including:
  - a. operating transients
  - b. temperature gradients (e.g., thermal boundary layers)
  - c. allowances for uncertainties in design parameters and physical data.

#### Particulate Matter Characteristics

The particulate matter originates from the ash constituents in the coal and from the injected seed. Throughout the flow path of the exhaust gases from the MHD generator exit to the stack, there is a very large number of compounds which can be formed in the gaseous, liquid and solid states. Of primary interest are those compounds which are first formed in the liquid state and solidify as the particles are cooled. Table B-1 (ref. B-1) indicates the composition of the ash of Montana Rosebud coal expressed in terms of its mineral oxides. Of the components listed in Table B-1, the largest amounts are expected to be  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$ . The melting points of these two constituents are 3130 and 3720°F, respectively (ref. B-2). The melting point of  $\text{K}_2\text{SO}_4$  is reported to be 1956°F (ref. B-3). However,  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$  are not necessarily found in their pure form. For example, potassium or potassium compounds may combine with the liquid  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$  particles, which may lower their melting points. Furthermore, there are a number of compounds of potassium which may be formed which have melting points much lower than that of  $\text{K}_2\text{SO}_4$ . Actually, there may be a large number of species of complex compounds formed in the combustion and subsequent condensation and cooling processes.

Since there are a large number of possible low melting point compounds, it is important to know which would survive under the downstream conditions experienced in the MHD gas stream. Because of the lack of extensive experimental data under actual MHD power plant conditions, it has been necessary to review data from conventional power plant experience as well as existing publications of MHD research and development programs.

Table B-I - Ash Composition for Montana Rosebud Coal

Constituent	Percent by Weight
SiO <sub>2</sub>	37.6
Al <sub>2</sub> O <sub>3</sub>	17.3
Fe <sub>2</sub> O <sub>3</sub>	5.1
TiO <sub>2</sub>	0.7
P <sub>2</sub> O <sub>5</sub>	0.4
CaO	11.0
MgO	4.0
Na <sub>2</sub> O	3.1
K <sub>2</sub> O	0.5
SO <sub>3</sub>	17.5

Table B-II - Ash Fusion Temperatures For Montana Rosebud Coal

Category	Temperature Range (°F)
Initial Deformation Temp. (°F)	1960 to 2420
Softening Temp. (°F)	1990 to 2470
Fluid Temp. (°F)	2080 to 2480

Ash fusion temperatures for many coals have been determined by standard ASTM testing procedures. There are four critical temperatures related to ash fusibility, defined as follows:

- a) Initial deformation temperature, at which the first rounding of the apex of the cone occurs.
- b) Softening temperature, at which the cone has fused down to a spherical lump in which the height is equal to the width at the base.
- c) Hemispherical temperature, at which the cone has fused down to a hemispherical lump at which point the height is one half the width of the base.
- d) Fluid temperature, at which the fused mass has spread out in a nearly flat layer with a maximum height of one-sixteenth inch.

Ash fusion temperatures for Montana Rosebud coal, taken from ref. B-1, are given in Table B-II.

Many low temperature melting compounds can be identified in the combustion of coal. The following discusses three such compounds which are typical of species found in some combustion processes.

In conventional power plants, iron, in the metallic (Fe), ferrous ( $\text{FeO}$ ) or ferric ( $\text{Fe}_2\text{O}_3$ ) states, has a significant effect upon the ash softening temperature. Since the iron content of Montana Rosebud coal is only 5 percent (as  $\text{Fe}_2\text{O}_3$ ), the ash fusion temperatures are expected to be substantially higher than the melting point of  $\text{K}_2\text{SO}_4$ . Therefore, attention must be focused on potassium compounds.

Potassium is not present in significant quantities in most solid fuels used in conventional power plants compared to sodium, an element with characteristics similar to those of potassium. One of the primary causes of corrosion in conventional power plants has been found (ref. B-4) to be the presence of alkali iron trisulfates, typically  $\text{Na}_3\text{Fe}(\text{SO}_4)_3$ . These trisulfates are molten at tem-



peratures as low as 650 to 750°F. However, the trisulfates are not found at temperatures above 1250°F and would not present a problem for a heat exchanger operating at a higher gas temperature range. As the temperature in the heater may likely drop below 1250°F at the low temperature end of the heater, the potential effects should be considered in future investigations.

Experiments have been conducted in MHD R&D programs to investigate corrosion due to seed deposits (ref. B-3). It has been found that, in the presence of  $\text{SO}_3$ , a melt was formed containing  $\text{K}_2\text{S}_2\text{O}_7$  in  $\text{K}_2\text{SO}_4$  in the temperature range 764 to 935°F. However, the formation of  $\text{K}_2\text{S}_2\text{O}_7$  requires a large concentration of  $\text{SO}_3$ . The equilibrium concentration of  $\text{SO}_3$  depends upon the temperatures and upon the concentrations of  $\text{SO}_2$  and  $\text{O}_2$ . The formation of  $\text{SO}_3$  is too slow to allow it to reach but a small fraction of its equilibrium concentration in the gas stream. The reason for the formation of the  $\text{K}_2\text{S}_2\text{O}_7$ - $\text{K}_2\text{SO}_4$  melt on surface deposits is that there is sufficient time to approach chemical equilibrium. For particles in the gas stream under conditions expected in the MHD power plant, the formation of a  $\text{K}_2\text{S}_2\text{O}_7$ - $\text{K}_2\text{SO}_4$  melt is expected to be negligible.

In the examples cited in the preceding paragraphs several compounds are indicated whose melting points are higher than that of  $\text{K}_2\text{SO}_4$  and several whose melting points are below that of  $\text{K}_2\text{SO}_4$ . However, the compounds with melting points lower than that of  $\text{K}_2\text{SO}_4$  do not appear to play a role in determining the phase state of particles in the regions where the gas temperature is above 1250°F. The compound  $\text{K}_2\text{CO}_3$  has a melting point below that of  $\text{K}_2\text{SO}_4$ , but according to the specifications presented in Appendix A (Tables A-II, A-III), the equilibrium composition of the gas stream does not contain an appreciable amount of  $\text{K}_2\text{CO}_3$ . Therefore,  $\text{K}_2\text{SO}_4$  is identified as the compound which would determine the temperature at which the particles would essentially be solid because it has a substantially lower melting point than the other gas stream constituents listed in Table A-II and A-III.

## Heat Transfer Model and Analysis

A heat transfer model has been developed to estimate the difference between the melting point of the particle substance and the gas temperature surrounding the particle at the instant at which the particle becomes completely solid. The model is described in Appendix C and the results are plotted in Figures C-2 and C-3. Figure C-3 is a plot of the dimensionless parameter

$$N_f = c_p \Delta T^* / H_f$$

where  $c_p$  is the specific heat capacity of the particle material,  $H_f$  is its latent heat of fusion and  $\Delta T^*$  is the difference between the melting point temperature and the temperature of the surrounding gas at the instant of complete solidification. This parameter is plotted against the dimensionless parameter

$$N_D = D \sqrt{\frac{\rho c_p G}{6Nu k_g H_f}}$$

where  $D$  is the particle diameter,  $Nu$  is the Nusselt number for convective heat transfer,  $k_g$  is the thermal conductivity of the gas,  $\rho$  is the particle density and  $G$  is the rate of change of the temperature of the gas surrounding the particle. The rate of change is equal to the product of the gas velocity and the temperature gradient in the direction of the flow.

Figure C-2 is a plot of the temperature difference  $\Delta T^*$  vs. particle diameter for particles of potassium sulfate for a family of values of the parameter  $G$ . According to reference B-5, the particle diameters are predicted to be less than 15 microns. For a gas stream with a velocity of 30 ft/sec in which the temperature is decreasing at a constant rate of 15 degrees per foot, this corresponds to a value of  $\Delta T^*$  of 15°F. This means that the potassium sulfate particles with diameters less than 15 microns would be solidified to the core by the time the gas stream has reached a temperature which is 15°F below the melting point. The resultant gas temperature is therefore predicted to be 1941°F.

Although much of the MHD research literature reports measured or calculated particle diameters of  $15\text{ }\mu\text{m}$  or less, others (ref. B-6) show particle sizes as high as  $90\text{ }\mu\text{m}$  in diameter. Although these particles are not specifically identified as  $\text{K}_2\text{SO}_4$ , it is seen from Figure C-2 in Appendix C, that the  $\Delta T^*$  for potassium sulfate particles with diameters of  $90\text{ }\mu\text{m}$  would be  $85^\circ\text{F}$  for  $30\text{ ft/sec}$  gas velocity and  $15^\circ\text{F/ft}$  temperature gradient. This corresponds to a gas temperature of  $1871^\circ\text{F}$ .

#### Heat Exchanger Design Considerations

By means of the preceding heat transfer analysis a gas temperature for particle solidification can be estimated, based upon values assumed for gas velocity, temperature gradient in the flow direction, particle size distribution and the physical properties of the particle substance and the gas. Although conservative assumptions were made in the development of the heat transfer model (e.g.  $\text{Nu} = 2$ ), uncertainty remains in estimates of the particle size distribution and substantial deviations in particle size from the predicted distribution may have a large effect on the predicted gas temperature for particle solidification. On the other hand, a particle with a solid shell and a molten core may be equivalent to a solid particle in terms of its behavior in relation to the surfaces of a ceramic heat exchanger.

Practically, several factors related to the operation of the MHD power plant must be considered in developing a practical heat exchanger design. Among these are:

1. Transients in operating conditions

- a. Variations in  $\Delta T^*$  due to variations in the parameters which affect  $\Delta T^*$ .
- b. Variations in the gas temperature at the entrance to the heat exchanger.
- c. Capability of heat exchanger surfaces to withstand liquid particles for brief periods.

2. Deviations in actual conditions during steady-state operation from conditions stipulated or assumed in the design such as non-equilibrium, supersaturation and effects of unpredictable chemical compound formation. Although the analysis and recommendations are being made on the basis of equilibrium conditions, it is probable that non-equilibrium compositions exist in fact.
3. Non-uniform temperature profiles (temperature gradients perpendicular to the flow direction).
4. Effect of addition of secondary air to the gas stream in the vicinity in which condensation and solidification of  $K_2SO_4$  occur.

Based on these considerations, it is projected that the intermediate air heater would be designed for a maximum gas inlet temperature in the range of 1870°F - 1940°F. The selection of a single design point depends on the margin of safety and conservatism that is desired and to allow for transient and other unpredictable conditions that may be encountered.

Reference for Appendix B

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- B-4. Reid, W. T.: External Corrosion and Deposits - Boilers and Gas Turbines. American Elsevier Publishing Co., New York, 1971.
- B-5. Im, K. "Nucleation and Evolution of Slag Droplets in Coal Combustion", Petrick, M., Tempelmeyer, K. and Johnson, T., MHD Balance of Plant Technology Project - First Quarterly Report, ANL/MHD-78-3.
- B-6. Dicks, J. B., Crawford, L. W., Kornstedt, K. W., "Direct Fired MHD Power Generation", ASME Paper No. 73-WA/Ener-2.

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APPENDIX C

SIMPLIFIED MATHEMATICAL MODEL OF  
PARTICLE SOLIDIFICATION IN AN MHD GAS STREAM

APPENDIX C

SIMPLIFIED MATHEMATICAL MODEL  
OF PARTICLE SOLIDIFICATION IN AN MHD GAS STREAM

A model is developed which presents a relationship between the MHD gas temperature, at the point at which freezing of an entrained liquid particle is complete, and the physical and thermodynamic characteristics and the temperature history of the particle and the gas. The model is applied to potassium sulfate and the results are used in arriving at the acceptable temperature range of the MHD gas stream for designing the intermediate temperature ceramic heaters.

The following assumptions are made:

1. particles are spherical and of pure composition (e.g., chemically pure  $K_2SO_4$ )
2. particle has a high thermal conductivity such that heat transfer from the particle is controlled by convection from its surface, and therefore the temperature is constant throughout the particle material
3. heat transfer from the particle by radiation is not significant
4. the particle moves with the same average velocity and direction as the gas
5. there is no condensation of vapor onto the particle during solidification
6. the temperature of the MHD gas decreases linearly with distance and the velocity of the gas is constant during solidification.

From the last assumption, the gas temperature  $T_g$  as a function of distance  $x$  is

$$T_g = T_{gi} - cx$$

where  $T_{gi}$  is taken at the point at which fusion of the particle commences (time  $t = 0$ ). Since the velocity  $v$  is constant,

$$x = vt$$

$$T_g = T_{gi} - Gt \quad (\text{eq. C-1})$$

where  $G = cv = - \frac{dT}{dt} g$

The gas temperature is plotted in Figure C-1 along with the temperature of the particle  $T_p$  as it passes through the melting point  $T_{mp}$  (from  $t = 0$  to  $t = t^*$ ). The temperature difference  $T_p - T_g$  during solidification is given by

$$\Delta T = T_p - T_g = T_{mp} - T_{gi} + Gt$$

$$\Delta T = \Delta T_i + Gt \quad (\text{eq. C-2})$$

The initial temperature difference  $\Delta T_i$  can be related to the system parameters by a heat balance of the particle prior to reaching the melting point. The rate of heat transfer from the particle as it cools is

$$q = hA (T_p - T_g)$$

which must equal



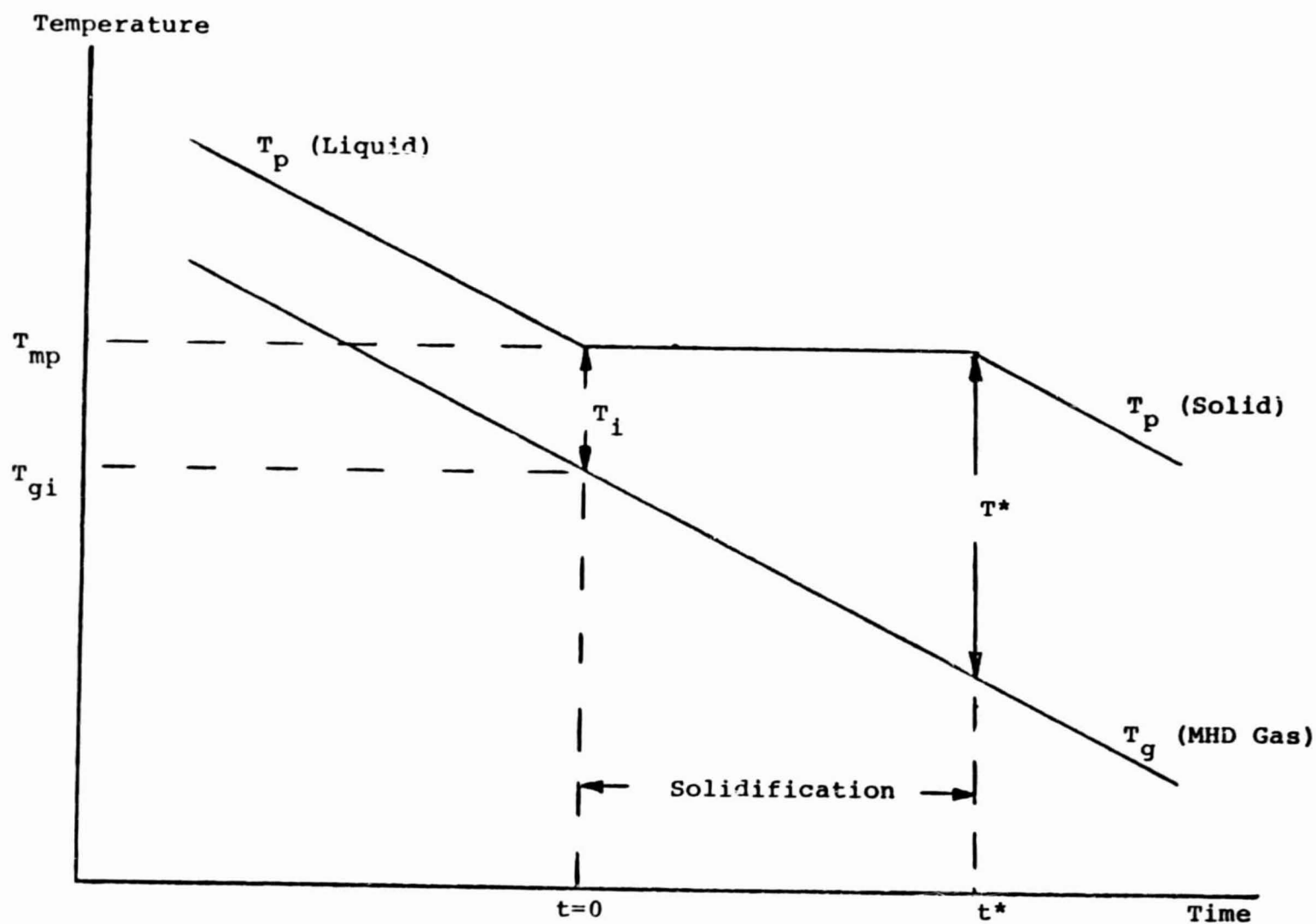


Figure C-1. MHD Gas and Particle Temperature History

$$q = mc_p \frac{dT_p}{dt}$$

Rearranging and using eq. C-1 for  $T_g$ ,

$$\frac{dT_p}{dt} = \frac{-hA}{mc_p} (T_p - T_{gi} + Gt)$$

or,

$$\frac{d}{dt} (T_p - T_{gi}) + \frac{hA}{mc_p} (T_p - T_{gi}) = \frac{-hAG}{mc_p} t$$

which has the solution,

$$T_p - T_{gi} = -Gt + \frac{mc_p G}{hA} (1 - e^{-(hAt/mc_p)})$$

If the particle has existed under these conditions for a relatively long time, the transient term drops out of the above equation, leaving,

$$T_p - T_{gi} + Gt = \frac{mc_p G}{hA}$$

$$T_p - T_g = \frac{mc_p G}{hA}$$

which at time  $t = 0$  is  $\Delta T_i$ . Then eq. C-2 becomes,

$$\Delta T = \frac{mc_p}{hA} + Gt \quad (\text{eq. C-3})$$

A heat balance during solidification of the particle gives

$$Q = mH_f = \int_0^{t^*} hA \Delta T dt$$

where  $H_f$  is the heat of fusion of the pure substance. Substituting for  $\Delta T$  gives

$$mH_f = hA \int_0^{t^*} \left( \frac{mc_p}{hA} + Gt \right) dt$$

$$mH_f = mc_p G t^* + \frac{hA G (t^*)^2}{2}$$

Solving the quadratic equation for  $t^*$  and using the particle diameter  $D$  and density  $\rho$ ,

$$t^* = \frac{-\rho_p D}{6h} + \left[ \left( \frac{\rho_p D}{6h} \right)^2 + \frac{\rho_f D}{3hG} \right]^{1/2}$$

The convective heat transfer coefficient  $h$  for spherical particles moving with a gas stream can be characterized by Nusselt number = 2, which is the lower

limit of heat transfer, approaching pure conduction (See note C-1). A value of  $Nu=3$  has also been used for particles in an MHD combustor environment (See note C-2). However,  $Nu=2$  is the more conservative value for the purposes of this investigation since a lower heat transfer rate will result in a longer solidification time. Then,

$$h = \frac{Nu k}{D} = \frac{2k}{D}$$

and

$$t^* = \frac{-\rho_p^c D^2}{12k_g} + \left[ \left( \frac{\rho_p^c D}{12k_g} \right)^2 + \frac{\rho_f^H D}{6k_g G} \right]^{1/2} \quad (\text{eq. C-4})$$

The following values for  $K_2SO_4$  in MHD gas were used:

$$\begin{aligned} \rho (K_2SO_4) &= 166 \text{ lbm/ft}^3 \text{ (See note C-3)} \\ c_p (K_2SO_4) &= 0.20 \text{ Btu/lbm-}^\circ\text{F (See note C-4)} \\ H_f (K_2SO_4) &= 83.7 \text{ Btu/lbm (See note C-5)} \\ k_g (\text{MHD gas}) &= 0.043 \text{ Btu/hr-ft-}^\circ\text{F (See note C-6)} \end{aligned}$$

Substitution in eq. C-4 yields

$$t^* = -1610 \frac{D^2 \text{ sec}}{\text{in}^2} + \left( 2.59 \times 10^6 \frac{D^4 \text{ sec}^2}{\text{in}^4} + 1.35 \times 10^6 \frac{D^2 \text{ sec-}^\circ\text{F}}{G \text{ in}^2} \right)^{1/2} \quad (\text{eq. C-5})$$

The final temperature differences  $\Delta T^*$  are calculated from equation C-2 with  $t = t^*$  and are plotted in Figure C-2 for various values of  $D$  and  $G$ . The range of particle diameters expected was obtained from Argonne National

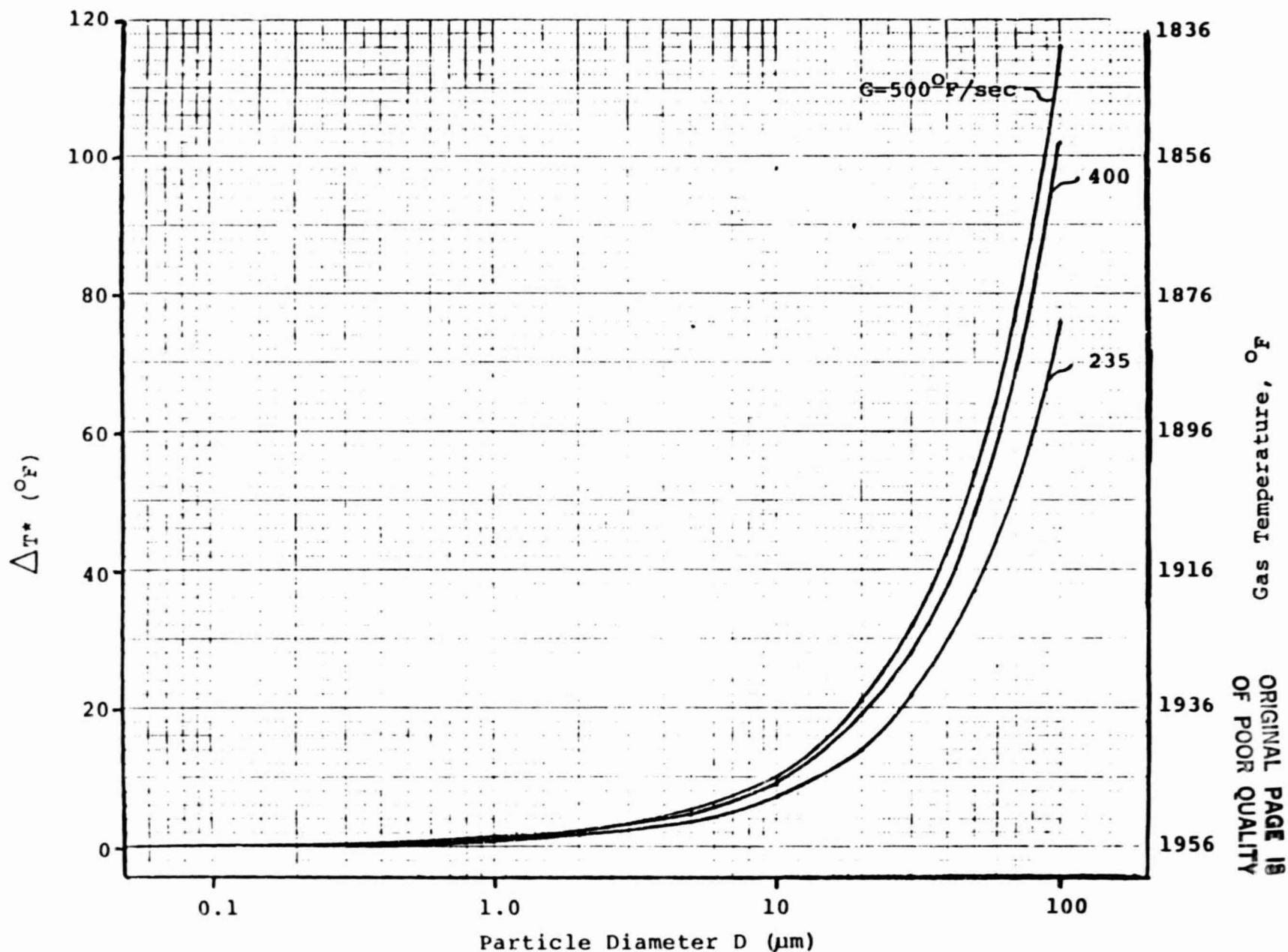


Figure C-2.  $T^*$  vs. Particle Diameter  $D$  and Gas Temperature Gradient  $G$

Laboratory particle growth model in an MHD channel (See note C-7). The values of the gas temperature-time gradient were taken from reference C-8.

An expression for  $\Delta T^*$  for any spherical particle can be obtained by combining equations C-2 and C-4. By rearranging terms, two dimensionless groups are obtained, as follows

$$N_D = \frac{D}{\left( \frac{6 N_{uk} H_g}{\rho C_p G} \right)^{1/2}} \quad \text{(dimensionless diameter)}$$

$$N_T = \frac{T^*}{\left( \frac{H_f}{C_p} \right)} \quad \text{(dimensionless temperature difference)}$$

The relationship between  $N_D$  and  $N_T$  is,

$$N_T = (N_D^4 + 2N_D^2)^{1/2}$$

and is plotted in Figure C-3.

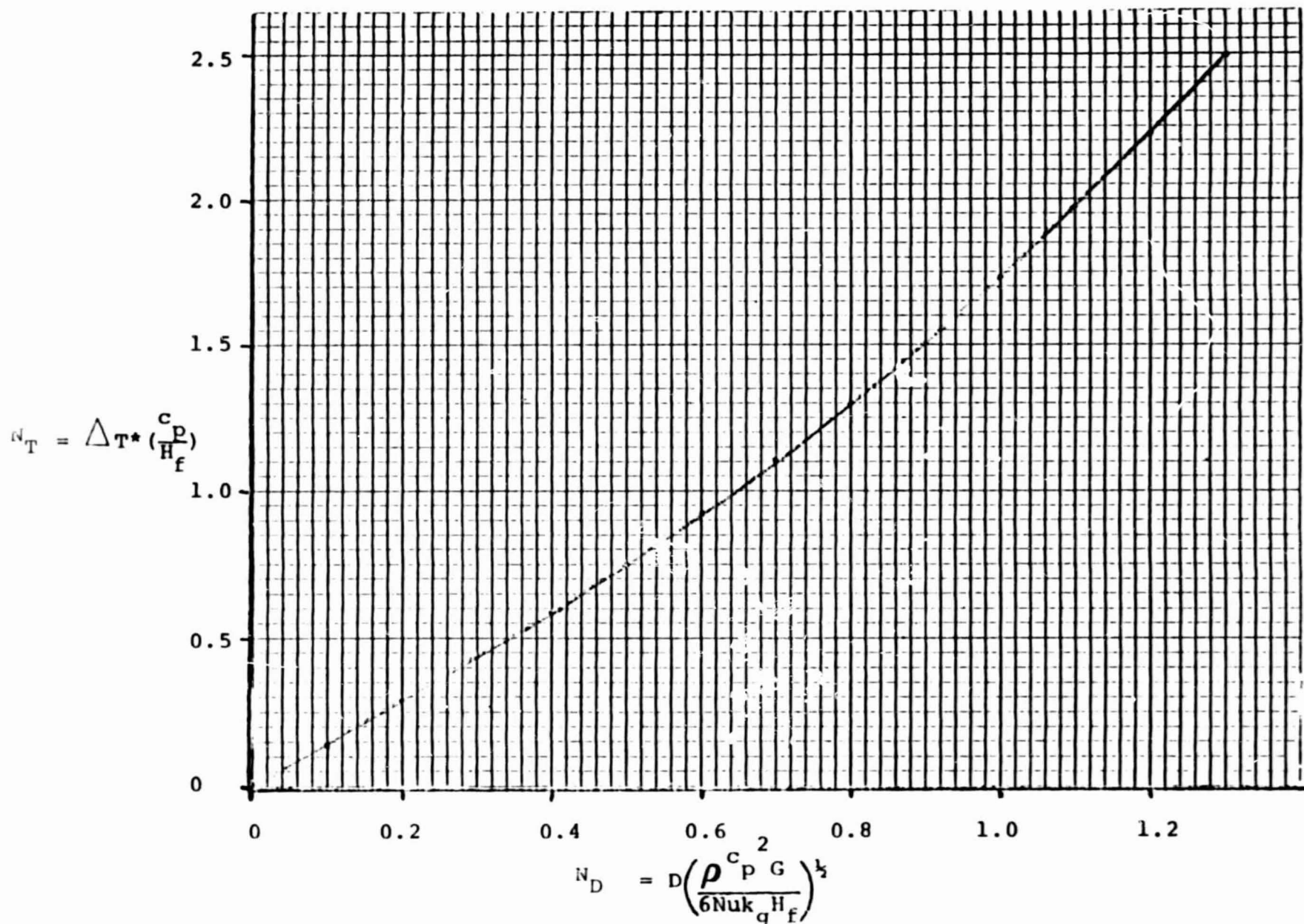


Figure C-3. Dimensionless Plot of Particle Solidification Model

Notes and References for Appendix C

- C-1. a) T.W. Hastings and A.F. Sarofin, "Char Gasification and Ash Volatization in Single-Stage and Two-Stage Coal-Fired MHD Combustors" in Seventh International Conference on MHD Electrical Power Generation, Vol. II, p. 473.  $Nu = 2$  was used for spherical particles  $10 \text{ } \mu\text{m} < D < 150 \text{ } \mu\text{m}$ .  
b) Zenz and Othmer, Fluidization and Fluid Particle Systems, pp. 421-423. Derivation of  $Nu = 2$  pure conduction.
- C-2. Heywood and Womack, Open Cycle MHD Power Generation, p. 648.
- C-3. Perry, Engineering Manual, 3rd ed., p. 3-10. Density for solid  $K_2SO_4$  is used for both liquid and solid phases.
- C-4. Heywood and Womack, *ibid.*, p. 648.
- C-5. Perry, *ibid.*, p. 3-10.
- C-6. Babcock and Wilcox, Steam/Its Generation and Use, 39th ed., p. 4-4. Thermal conductivity of flue gas from coal at  $2000^\circ\text{F}$ .
- C-7. K. Im and P. Chung, "Nucleation and Evolution of Slag Droplets in Coal Combustion," in Argonne National Laboratory/MHD-78-3, MHD Balance of Plant Technology Report, First Quarterly Report, p. 21.
- C-8. Avco Everett Research Laboratory, Inc., Engineering Test Facility Conceptual Design, Final Report, Part 2, June 1978, pp. 535-537 and fig. 2-140. Cooling rates were calculated from data presented and correspond to location as follows:
- $235^\circ\text{F}/\text{sec}$  - air heater furnace  
 $400^\circ\text{F}/\text{sec}$  - radiant boiler  
 $500^\circ\text{F}/\text{sec}$  - seed recovery furnace (superheater)



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APPENDIX D

COST ESTIMATE FOR FIXED BED  
REGENERATIVE HEATER SYSTEM

COST ESTIMATE  
FOR  
ITOH FIXED-BED  
REGENERATIVE HEATER

PROJECT TITLE: CONCEPTUAL DESIGN OF ITOH  
FOR OPEN-CYCLE MHD POWER PLANT  
FLUIDYNE JOB NO.: 1296

SHEET 1 OF 21  
DATE: July 1981

SHEET NO.	DESCRIPTION	QTY.	WEIGHT	UNIT OF MEASURE	UNIT PRICE	TOTALS (\$000)
	Summary					
2-4	Heaters - Shells					1525
2-4	Heaters - Insulation Materials					270
2-4	Heaters - Insulation Installation				6612	326
2-4	Heaters - Refractory Matrix					2939
2-4	Heaters - Matrix Support System					1552
5-8	MHD Gas In Ducting and Manifolds - Insulated					1003
9-12	MHD Gas Out Ducting and Manifolds - Insulated				2283	787
13-17	Oxidant Ducting and Manifolds - Insulated					423
18	Sequencing Valves					6548
19	Major Expansion Joints					462
20	Support Structure					1639
21	Controls and Inst./Erection and Assembly					1754
						19298

COST ESTIMATE

FOR

ITOH FIXED-BED

REGENERATIVE HEATER

PROJECT TITLE: CONCEPTUAL DESIGN OF ITOH  
FOR OPEN-CYCLE MHD POWER PLANT

FLUIDYNE JOB NO.: 1296

SHEET 2 OF 21

DATE: July 1981

SHEET NO.	DESCRIPTION	QTY.	WEIGHT	UNIT OF MEASURE	UNIT PRICE	TOTALS (\$000)
	Vessel - Upper Dome		Pounds Each			
	Steel $\rho=500 \text{ LBM/FT}^3$ $v=116.4 \text{ FT}^3$					
	Mat'l	4	58200	.35\$/LBM	20370	81
	Labor	4		1.25\$/LBM	72750	291
	Insulation Material					
	KS-4 $\rho=121 \text{ LBM/FT}^3$ $v=232.7 \text{ FT}^3$	4	28157	.28\$/LBM	7885	32
	CASTABLE 20 $\rho=36 \text{ LBM/FT}^3$ $v=325.9 \text{ FT}^3$	4	11732	.60\$/LBM	7040	28
	Calcium Silicate $\rho=46 \text{ LBM/FT}^3$ $v=46.6 \text{ FT}^3$	4	2144	1.05\$/LBM	2250	9
	Insulation Installation					
	KS-4	4		52.00\$/FT <sup>2</sup>	12100	48
	Castable 20	4		52.00\$/FT <sup>2</sup>	16945	68
	Calcium Silicate	4		22.75\$/FT <sup>2</sup>	1060	4
			Total Pounds			
			400932			561

# COST ESTIMATE

FOR

ITOH FIXED-BED

REGENERATIVE HEATER

PROJECT TITLE: CONCEPTUAL DESIGN OF ITOH  
FOR OPEN-CYCLE MHD POWER PLANT

FLUIDYNE JOB NO.: 1296

SHEET 3 OF 21

DATE: July 1981

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SHEET NO.	DESCRIPTION	QTY.	WEIGHT	UNIT OF MEASURE	UNIT PRICE	TOTALS (\$000)
	Vessel - Bed		Pounds Each			
	Steel $\rho=500 \text{ LBM/FT}^3$ $v=331.6 \text{ FT}^3$					
	Mat'l	4	165800	.35\$/LBM	58030	232
	Labor	4		1.25\$/LBM	207250	829
	Insulation and Checker Material					
	KS-4 $\rho=121 \text{ LBM/FT}^3$ $v=225.3 \text{ FT}^3$	4	27261	.28\$/LBM	7635	31
	Castable 20 $\rho=36 \text{ LBM/FT}^3$ $v=720.7 \text{ FT}^3$	4	25945	.60\$/LBM	15570	62
	Calcium Silicate $\rho=46 \text{ LBM/FT}^3$ $v=132.6 \text{ FT}^3$	4	6100	1.05\$/LBM	6405	26
	Checkers $\rho=150 \text{ LBM/FT}^3$ $v=9300 \text{ FT}^3$	4	1395000	.31\$/LBM	432450	1730
	Insulation and Checker Installation					
	KS-4	4		26.00\$/FT <sup>3</sup>	5860	2
	Castable 20	4		26.00\$/FT <sup>3</sup>	18740	75
	Calcium Silicate	4		22.75\$/FT <sup>3</sup>	3015	12
	Checkers	4		32.50\$/FT <sup>3</sup>	302250	1209
			Total Pounds			
			6480424			4229

COST ESTIMATE  
FOR  
ITOH FIXED-BED  
REGENERATIVE HEATER

PROJECT TITLE: CONCEPTUAL DESIGN OF ITOH  
FOR OPEN-CYCLE MHD POWER PLANT  
FLUIDDYNE JOB NO.: 1296

SHEET 4 OF 21

DATE: July 1981

SHEET NO.	DESCRIPTION	QTY.	WEIGHT	UNIT OF MEASURE	UNIT PRICE	TOTALS (\$000)
	Vessel - Lower		Pounds Each			
	Steel $\rho=500 \text{ LBM/FT}^3$ $v=28.84 \text{ FT}^3$					
	Mat'l	4	14420	.35\$/LBM	5050	20
	Labor	4		1.25\$/LBM	18025	72
	Insulation Material					
	Lightweight Castable $\rho=36 \text{ LBM/FT}^3$ $v=1213.3 \text{ FT}^3$	4	43678	.46\$/LBM	20090	80
	Calcium Silicate $\rho=46 \text{ LBM/FT}^3$ $v=11.63 \text{ FT}^3$	4	535	1.05\$/LBM	560	2
	Insulation Installation					
	Lightweight Castable	4		19.50\$/FT	23660	95
	Calcium Silicate	4		22.75\$/FT	265	1
	Matrix Support System					
	Materials	4		See Notes	341600	1366
	Labor	4		See Notes	46500	186
			Total Pounds			
			234532			1822

COST ESTIMATE  
FOR  
ITOH FIXED-BED  
REGENERATIVE HEATER

PROJECT TITLE: CONCEPTUAL DESIGN OF ITOH  
FOR OPEN-CYCLE MHD POWER PLANT  
FLUIDYNE JOB NO.: 1296

SHEET 5 OF 21

DATE: July 1981

SHEET NO.	DESCRIPTION	QTY.	WEIGHT	UNIT OF MEASURE	UNIT PRICE	TOTALS (\$000)
	Main MHD Gas In Duct		Pounds Each			
	Steel $\rho=500 \text{ LBM/FT}^3$ $v=51.50 \text{ FT}^3$					
	Mat'l	1	25750	.35\$/LB	9015	9
	Labor	1		1.25\$/LB	32190	32
	Insulation Material					
	KS-4 $\rho=121 \text{ LBM/FT}^3$ $v=515 \text{ FT}^3$	1	62315	.28\$/LBM	17450	17
	Castable 20 $\rho=36 \text{ LBM/FT}^3$ $v=721 \text{ FT}^3$	1	25959	.60\$/LBM	15575	16
	Calcium Silicate $\rho=46 \text{ LBM/FT}^3$ $v=103 \text{ FT}^3$	1	4740	1.05\$/LBM	4975	5
	Insulation Installation					
	KS-4	1		26.00\$/FT <sup>3</sup>	13390	13
	Castable 20	1		26.00\$/FT <sup>3</sup>	18750	19
	Calcium Silicate	1		22.75\$/FT <sup>3</sup>	2345	2
			Total Pounds			
			118761			113

COST ESTIMATE  
FOR  
ITOH FIXED-BED  
REGENERATIVE HEATER

PROJECT TITLE: CONCEPTUAL DESIGN OF ITOH  
FOR OPEN-CYCLE MHD POWER PLANT  
FLUIDDYNE JOB NO.: 1296

SHEET 6 OF 21

DATE: July 1981

SHEET NO.	DESCRIPTION	QTY.	WEIGHT	UNIT OF MEASURE	UNIT PRICE	TOTALS (\$000)
	Central Collector-MHD Gas In		Pounds Each			
	Steel $\rho=500 \text{ LBM/FT}^3$ $v=505.60 \text{ FT}^3$					
	Mat'l	1	252800	.35\$/LBM	88480	88
	Labor	1		1.25\$/LBM	316000	316
	Insulation Material					
	KS-4 $\rho=121 \text{ LBM/FT}^3$ $v=1011 \text{ FT}^3$	1	122331	.28\$/LBM	34255	34
	Castable 20 $\rho=36 \text{ LBM/FT}^3$ $v=1416 \text{ FT}^3$	1	50976	.60\$/LBM	30585	31
	Calcium Silicate $\rho=46 \text{ LBM/FT}^3$ $v=202 \text{ FT}^3$	1	9292	1.05\$/LBM	9755	10
	Insulation Installation					
	KS-4	1		26.00\$/FT <sup>3</sup>	26286	26
	Castable 20	1		26.00\$/FT <sup>3</sup>	36816	37
	Calcium Silicate	1		22.75\$/FT <sup>3</sup>	4600	5
			Total Pounds			
			435399			547

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SHEET 7 OF 21  
DATE: July 1981

SHEET NO.	DESCRIPTION	QTY.	WEIGHT	UNIT OF MEASURE	UNIT PRICE	TOTALS (\$000)
	MHD Gas In Manifolds-From Central Collector		Pounds Each			
	Steel $\rho=500 \text{ LBM/FT}^3$ $v=22.74 \text{ FT}^3$					
	Mat'l	4	11370	.35\$/LBM	3980	16
	Labor	4		1.25\$/LBM	14215	59
	Insulation Material					
	KS-4 $\rho=121 \text{ LBM/FT}^3$ $v=227.4 \text{ FT}^3$	4	27515	.28\$/LBM	7705	31
	Castable 20 $\rho=36 \text{ LBM/FT}^3$ $v=318.4 \text{ FT}^3$	4	11462	.60\$/LBM	6875	28
	Calcium Silicate $\rho=46 \text{ LBM/FT}^3$ $v=45.5 \text{ FT}^3$	4	2093	1.05\$/LBM	2200	9
	Insulation Installation					
	KS-4	4		26.00\$/ $\text{FT}^3$	5910	24
	Castable 20	4		26.00\$/ $\text{FT}^3$	8280	33
	Calcium Silicate	4		22.75\$/ $\text{FT}^3$	1035	4
			Total Pounds			
			209760			204



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**SHEET 8 OF 21**

DATE: July 1981

160

COST ESTIMATE  
FOR  
ITOH FIXED-BED  
REGENERATIVE HEATER

PROJECT TITLE: CONCEPTUAL DESIGN OF ITOH  
FOR OPEN-CYCLE MHD POWER PLANT  
FLUIDDYNE JOB NO.: 1296

SHEET 9 OF 21

DATE: July 1981

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SHEET NO.	DESCRIPTION	QTY.	WEIGHT	UNIT OF MEASURE	UNIT PRICE	TOTALS (\$000)
	Main MHD Gas Out Duct		Pounds Each			
	Steel $\rho=500 \text{ LBM/FT}^3$ $v=51.50 \text{ FT}^3$					
	Mat'l	1	25750	.35\$/LBM	9015	9
	Labor	1		1.25\$/LBM	32190	32
	Insulation Material					
	KS-4 $\rho=121 \text{ LBM/FT}^3$ $v=515 \text{ FT}^3$	1	62315	.28\$/LBM	17450	17
	Castable 20 $\rho=36 \text{ LBM/FT}^3$ $v=412 \text{ FT}^3$	1	14832	.60\$/LBM	8900	9
	Calcium Silicate $\rho=46 \text{ LBM/FT}^3$ $v=103 \text{ FT}^3$	1	4738	1.05\$/LBM	4975	5
	Insulation Installation					
	KS-4	1		26.00\$/FT <sup>3</sup>	13390	13
	Castable 20	1		26.00\$/FT <sup>3</sup>	10710	11
	Calcium Silicate	1		22.75\$/FT <sup>3</sup>	2345	2
			Total Pounds			
			107635			98

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**SHEET 10 OF 21**

DATE: July 1981

162

## REGENERATIVE HEATER

FLUIDYNE JOB NO.: 1296

**SHEET 11 OF 21**

DATE: July 1981

SHEET NO.	DESCRIPTION	QTY.	WEIGHT	UNIT OF MEASURE	UNIT PRICE	TOTALS (\$000)
	MHD Gas Out Manifolds-To Central Collector		Pounds Each			
	Steel $\rho=500 \text{ LBM/FT}^3 \quad v=18.27 \text{ FT}^3$					
	Mat'l	4	9135	.35\$/LBM	3200	13
	Labor	4		1.25\$/LBM	11420	46
	Insulation Material					
	KS-4 $\rho=121 \text{ LBM/FT}^3 \quad v=182.7 \text{ FT}^3$	4	22107	.28\$/LBM	6190	25
	Castable 20 $\rho=36 \text{ LBM/FT}^3 \quad v=146.2 \text{ FT}^3$	4	5263	.60\$/LBM	3160	13
	Calcium Silicate $\rho=46 \text{ LBM/FT}^3 \quad v=16.5 \text{ FT}^3$	4	1679	1.05\$/LBM	1765	7
	Insulation Installation					
	KS-4	4		26.00\$/LBM	4750	19
	Castable 20	4		26.00\$/LBM	3800	15
	Calcium Silicate	4		22.75\$/LBM	830	3
			Total Pounds			
			152736			141

COST ESTIMATE  
FOR  
ITOH FIXED-BED  
REGENERATIVE HEATER

PROJECT TITLE: CONCEPTUAL DESIGN OF ITOH  
FOR OPEN-CYCLE MHD POWER PLANT  
FLUIDDYNE JOB NO.: 1296

SHEET 12 OF 21  
DATE: July 1981

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SHEET NO.	DESCRIPTION	QTY.	WEIGHT	UNIT OF MEASURE	UNIT PRICE	TOTALS (\$000)
	MHD Gas Out Ducts-From Heater Vessels		Pounds Each			
	Steel $\rho = 500 \text{ LBM/FT}^3 \quad v = 5.18 \text{ FT}^3$					
	Mat'l	8	2590	.35\$/LBM	915	7
	Labor	8		1.25\$/LBM	3240	26
	Insulation Material					
	KS-4 $\rho = 121 \text{ LBM/FT}^3 \quad v = 51.8 \text{ FT}^3$	8	6268	.28\$/LBM	1755	14
	Castable 20 $\rho = 136 \text{ LBM/FT}^3 \quad v = 41.4 \text{ FT}^3$	8	1490	.60\$/LBM	895	7
	Calcium Silicate $\rho = 46 \text{ LBM/FT}^3 \quad v = 10.4 \text{ FT}^3$	8	478	1.05\$/LBM	500	4
	Insulation Installation					
	KS-4	8		26.00\$/FT <sup>3</sup>	1350	11
	Castable 20	8		26.00\$/FT <sup>3</sup>	1075	9
	Calcium Silicate	8		22.75\$/FT <sup>3</sup>	235	2
			Total Pounds			
			86608			80

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DATE: July 1981

165

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SHEET 15 OF 21  
DATE: July 1981

166

## REGENERATIVE HEATER

FLUIDYNE JOB NO.: 1296

SHEET 16 OF 21

DATE: July 1981

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SHEET NO.	DESCRIPTION	QTY.	WEIGHT	UNIT OF MEASURE	UNIT PRICE	TOTALS (\$000)
	Main Oxidant Out Duct		Pounds Each			
	Steel $\rho=500 \text{ LBM/FT}^3$ $v=96.90 \text{ FT}^3$					
	Mat'l	1	48450	.35\$/LBM	16960	17
	Labor	1		1.25\$/LBM	60565	60
	Insulation Material					
	KS-4 $\rho=121 \text{ LBM/FT}^3$ $v=484.5 \text{ FT}^3$	1	58625	.28\$/LBM	16415	16
	Castable 20 $\rho=36 \text{ LBM/FT}^3$ $v=533. \text{ FT}^3$	1	19188	.60\$/LBM	11515	11
	Calcium Silicate $\rho=46 \text{ LBM/FT}^3$ $v=96.9 \text{ FT}^3$	1	4457	1.05\$/Lbm	4680	5
	Insulation Installation					
	KS-4	1		26.00\$/FT <sup>3</sup>	12600	13
	Castable 20	1		26.00\$/FT <sup>3</sup>	13860	14
	Calcium Silicate	1		22.75\$/FT <sup>3</sup>	2205	2
			Total Pounds			
			130720			138



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DATE: July 1981

168

## REGENERATIVE HEATER

FLUIDYNE JOB NO.: 1296

SHEET 17 OF 21

DATE: July 1981

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SHEET NO.	DESCRIPTION	QTY.	WEIGHT	UNIT OF MEASURE	UNIT PRICE	TOTALS (\$000)
	Oxidant Out Ducts-From Heater Vessels		Pounds Each			
	Steel $\rho = 500 \text{ LBM/FT}^3$ $v = 28.60 \text{ FT}^3$					
	Mat'l	4	14300	35\$/LBM	5005	20
	Labor	4		1.25\$/LBM	17875	72
	Insulation Material					
	KS-4 $\rho = 121 \text{ LBM/FT}^3$ $v = 190.7 \text{ FT}^3$	4	23075	.28\$/LBM	6460	26
	Castable 20 $\rho = 36 \text{ LBM/FT}^3$ $v = 209.7 \text{ FT}^3$	4	7549	.60\$/LBM	4530	18
	Calcium Silicate $\rho = 46 \text{ LBM/FT}^3$ $v = 38.1 \text{ FT}^3$	4	1753	1.05\$/LBM	1840	7
	Insulation Installation					
	KS-4	4		26.00\$/LBM	4960	20
	Castable 20	4		26.00\$/LBM	5450	22
	Calcium Silicate	4		22.75\$/LBM	865	3
			Total Pounds			
			186708			188

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**SHEET 18 OF 21**

DATE: July 1981

170

## REGENERATIVE HEATER

FLUIDYNE JOB NO.: 1296

**SHEET 19 OF 21**

DATE: July 1981

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SHEET NO.	DESCRIPTION	QTY.	WEIGHT	UNIT OF MEASURE	UNIT PRICE	TOTALS (\$000)
	Major Expansion Joints					
	Gas Inlet Duct (116" DIA.)	8		As Noted*	23000	184
	Gas Outlet Duct (95" DIA.)	8		As Noted*	15500	124
	Air Inlet Duct (48" DIA.)	8		As Noted*	6000	48
	Air Outlet Duct (76" DIA.)	8		As Noted*	10600	85
	Pressurization Duct (18" DIA.)	4		As Noted*	2000	8
	De-pressurization Duct (24" DIA.)	4		As Noted*	3200	13
	*Scaled from earlier quotes.					
						462

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**SHEET 20 OF 21**

DATE: July 1981

172

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**SHEET 21 OF 21**

DATE: July 1981

173

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APPENDIX E

COST ESTIMATE FOR CERAMIC  
RECUPERATIVE HEATER SYSTEM

COST ESTIMATE  
FOR  
ITOH CERAMIC  
RECUPERATIVE HEATER

PROJECT TITLE: CONCEPTUAL DESIGN OF ITOH  
FOR OPEN-CYCLE MHD POWER PLANT  
FLUIDYNE JOB NO.: 1296

SHEET 1 OF 16

DATE: July 1981

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SHEET NO.	DESCRIPTION	QTY.	WEIGHT	UNIT OF MEASURE	UNIT PRICE	TOTALS (\$000)
	Summary					
2	Recuperator Tube Bundle					7,460
3	Recuperator Shell					274
3	Recuperator Insulation Materials					154
3	Recuperator Insulation Installation					140
4-6	MHD Gas In Duct & Manifold Insulated					2,206
7-9	MHD Gas Out Duct & Manifold Insulated					1,209
10-11	Oxidant In Duct & Manifold Insulated					113
12,13	Oxidant Out Duct & Manifold Insulated					275
14	Support Structure					600
15	Expansion Joints & Misc. Parts					348
16	Erection & Assembly					3,045
						15,824

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COST ESTIMATE  
FOR  
ITOH CERAMIC  
RECUPERATIVE HEATER

PROJECT TITLE: CONCEPTUAL DESIGN OF ITOH  
FOR OPEN-CYCLE MHD POWER PLANT  
FLUIDDYNE JOB NO.: 1296

SHEET 2 OF 16

DATE: July 1981

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SHEET NO.	DESCRIPTION	QTY.	WEIGHT	UNIT OF MEASURE	UNIT PRICE	TOTALS (\$000)
	Recuperator Tube Bundle			\$/Tube		
	Materials			Bundle		
	SiC Straight Tubes	20	124,400	31,100		622
	SiC "U" Tubes	20	30,000	35,800		716
	SiC Headers	20	6,000	4,100		82
	SiC - Metal Adapter	20	16,000	2,000		40
	Metal Supports & Flow Baffle*	20	4,000	9,000		160
	Bundle Assembly, Joining & Firing	20		292,000		5,840
	Est # 4 x SiC Matl. Costs					
	*Estimated at 10% of tube bundle weight.					
			Total lbs			
			180,400			7,460

COST ESTIMATE  
FOR  
ITOH CERAMIC  
RECUPERATIVE HEATER

PROJECT TITLE: CONCEPTUAL DESIGN OF ITOH  
FOR OPEN-CYCLE MHD POWER PLANT  
FLUIDYNE JOB NO.: 1296

SHEET 3 OF 16

DATE: July 1981

ORIGINAL PAGE IS  
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SHEET NO.	DESCRIPTION	QTY.	WEIGHT	UNIT OF MEASURE	UNIT PRICE	TOTALS (\$000)
	Recuperator Shell (20 Units)					
	Steel $\rho=500 \text{ lbs/ft}^3$					
	A=2,960 $\text{ft}^2$					
	V= 311 $\text{ft}^3$ (3/8 Wall)					
	Mat'l	1	171,100	\$ .35/lb	59,900	60
	Labor	1		1.25/lb	213,900	214
	Insulation Material					
	KS-4 $\rho=121 \text{ lb/ft}^3$	1	251,100	.28/lb	70,300	71
	Castable 20 $\rho=36 \text{ lb/ft}^3$	1	104,600	.60/lb	62,700	63
	Calcium Silicate $\rho=46 \text{ lb/ft}^3$	1	19,100	1.05/lb	20,000	20
	Insulation Installation					
	KS-4 V=2,075 $\text{ft}^3$	1		26.00/ft	53,950	54
	Castable 20 V=2,905 $\text{ft}^3$	1		26.00/ft	75,530	76
	Calcium Silicate V=415 $\text{ft}^3$	1		22.75/ft	9,441	10
			Total lbs			
			545,900			568

COST ESTIMATE  
FOR  
ITOH CERAMIC  
RECUPERATIVE HEATER

PROJECT TITLE: CONCEPTUAL DESIGN OF ITOH  
FOR OPEN-CYCLE MHD POWER PLANT  
FLUIDYNE JOB NO.: 1296

SHEET 4 OF 16

DATE: July 1981

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SHEET NO.	DESCRIPTION	QTY.	WEIGHT	UNIT OF MEASURE	UNIT PRICE	TOTALS (\$000)
	MHD Gas In Duct 1/2" Wall					
	Steel $\rho=500 \text{ lb/ft}^3$					
	$A=2,326 \text{ ft}^2$					
	$V=96.9 \text{ ft}^3 + 10\% \text{ (Stiffeners)}$					
	$V=107 \text{ ft}^3$					
	Mat'l	1	52,500	\$ .35/lb	18,725	19
	Labor	1		1.25/lb	66,875	67
	Insulation Material					
	KS-4 $\rho=121 \text{ lb/ft}^3$	1	58,600	.28/lb	16,408	17
	Castable 20 $\rho=16 \text{ lb/ft}^3$	1	24,400	.60/lb	14,640	15
	Calcium Silicate $\rho=46 \text{ lb/ft}^3$	1	4,500	1.05/lb	4,725	5
	Insulation Installation					
	KS-4 $V=195 \text{ ft}^3$	1		26.00/ft	12,610	13
	Castable 20 $V=678 \text{ ft}^3$	1		26.00/ft	17,628	18
	Calcium Silicate $V=97 \text{ ft}^3$	1		22.75/ft	2,207	3
			Total Pounds			
			141,000			157

COST ESTIMATE  
FOR  
ITOH CERAMIC  
RECUPERATIVE HEATER

PROJECT TITLE: CONCEPTUAL DESIGN OF ITOH  
FOR OPEN-CYCLE MHD POWER PLANT  
FLUIDDYNE JOB NO.: 1296

SHEET 5 OF 16  
DATE: July 1981

ORIGINAL PAGE IS  
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SHEET NO.	DESCRIPTION	QTY.	WEIGHT	UNIT OF MEASURE	UNIT PRICE	TOTALS (\$000)
	MID Gas In Crossover 3/8 Wall					
	Steel $\rho=500 \text{ lbs/ft}^3$					
	$A=2.170 \text{ ft}^2$					
	$V=67.8 \text{ ft}^3 + 10\% \text{ (Stiffeners)}$					
	$V=74.6 \text{ ft}^3$					
	Mat'l	1	37,300	\$ .35/lb	13.055	14
	Labor	1		1.25/lb	46.625	47
	Insulation Materials					
	KS-4 $\rho=121 \text{ lb/ft}^3$	1	54,702	.28/lb	15,317	16
	Castable 20 $\rho=36 \text{ lb/ft}^3$	1	29,118	.60/lb	17,471	18
	Calcium Silicate $\rho=46 \text{ lb/ft}^3$	1	4,186	1.05/lb	4,395	5
	Insulation Installation					
	KS-4 $V=452 \text{ ft}^3$	1		26.00/ft	11,752	12
	Castable 20 $V=633 \text{ ft}^3$	1		26.00/ft	16,458	17
	Calcium Silicate $V=91 \text{ ft}^3$	1		22.75/ft	2,070	3
			Total Pounds			
			125,306			132

COST ESTIMATE  
FOR  
ITOH CERAMIC  
RECUPERATIVE HEATER

PROJECT TITLE: CONCEPTUAL DESIGN OF ITOH  
FOR OPEN-CYCLE MHD POWER PLANT  
FLUIDDYNE JOB NO.: 1296

SHEET 6 OF 16

DATE: July 1981

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SHEET NO.	DESCRIPTION	QTY.	WEIGHT	UNIT OF MEASURE	UNIT PRICE	TOTALS (\$000)
	MHD Gas In Manifold 3/8 Wall					
	Steel $\rho=500 \text{ lb/ft}^3$					
	$A=33,696 \text{ ft}^2$					
	$V=1,053 \text{ ft}^3 + 10\% \text{ (Stiffeners)}$					
	$V=1,158 \text{ ft}^3$					
	Mat'l	1	579,150	\$ .35/lb	202,702	203
	Labor	1		1.25/lb	723,937	724
	Insulation Materials					
	KS-4 $\rho=121 \text{ lb/ft}^3$	1	849,420	.28/lb	237,937	238
	Castable 20 $\rho=36 \text{ lb/ft}^3$	1	353,808	.60/lb	212,285	213
	Calcium Silicate $\rho=46 \text{ lb/ft}^3$	1	64,584	1.05/lb	67,813	68
	Insulation Installation					
	KS-4 $V=7,020 \text{ ft}^3$	1		26.00/ft	182,520	183
	Castable 20 $V=9,828 \text{ ft}^3$	1		26.00/ft	255,583	256
	Calcium Silicate $V=1,404 \text{ ft}^3$	1		22.75/ft	31,941	32
			Total Pounds			
			1,846,962			1,917

COST ESTIMATE  
FOR  
ITOH CERAMIC  
RECUPERATIVE HEATER

PROJECT TITLE: CONCEPTUAL DESIGN OF ITOH  
FOR OPEN-CYCLE MHD POWER PLANT  
FLUIDYNE JOB NO.: 1296

SHEET 7 OF 16

DATE: July 1981

SHEET NO.	DESCRIPTION	QTY.	WEIGHT	UNIT OF MEASURE	UNIT PRICE	TOTALS (\$000)
	MHD Gas Out Duct					
	Steel $\rho=500 \text{ lbs/ft}^3$					
	$A=2.496 \text{ ft}^2$					
	$V=104 + 10\% \text{ (Stiffeners)}$					
	$V=114.4 \text{ ft}^3$					
	Mat'l	1	57,200	35/lb	20,020	20
	Labor	1		1.25/lb	71,500	72
	Insulation Materials					
	KS-4 $\rho=121 \text{ lb/ft}^3$	1	62,920	28/lb	17,618	18
	Castable 20 $\rho=36 \text{ lb/ft}^3$	1	9,360	60/lb	5,616	6
	Calcium Silicate $\rho=46 \text{ lb/ft}^3$	1	4,784	1.05/lb	5,023	5
	Insulation Installation					
	KS-4 $V=520 \text{ ft}^3$	1		26.00/ft	13,520	14
	Castable 20 $V=260 \text{ ft}^3$	1		26.00/ft	6,760	7
	Calcium Silicate $V=104 \text{ ft}^3$	1		22.75/ft	2,366	3
			Total Pounds			
			134,264			145

COST ESTIMATE  
FOR  
ITOH CERAMIC  
RECUPERATIVE HEATER

PROJECT TITLE: CONCEPTUAL DESIGN OF ITOH  
FOR OPEN-CYCLE MHD POWER PLANT  
FLUIDYNE JOB NO.: 1296

SHEET 8 OF 16

DATE: July 1981

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SHEET NO.	DESCRIPTION	QTY.	WEIGHT	UNIT OF MEASURE	UNIT PRICE	TOTALS (\$000)
	MHD Gas Out Crossover 3/8 Wall					
	Steel $\rho=500 \text{ lbs/ft}^3$					
	$A=1,767 \text{ ft}^2$					
	$V=55.2 + 10\% \text{ (Stiffeners)}$					
	$V=60.7 \text{ ft}^3$					
	Mat'l	1	30,350	\$ .35/lb	10,623	11
	Labor	1		1.25/lb	37.938	38
	Insulation Materials					
	KS-4 $\rho=121 \text{ lb/ft}^3$	1	44,528	.28/lb	12,468	13
	Castable 20 $\rho=36 \text{ lb/ft}^3$	1	6,624	.60/lb	3,974	4
	Calcium Silicate $\rho=46 \text{ lb/ft}^3$	1	3,386	1.05/lb	3,555	4
	Insulation Installation					
	KS-4 $V=368 \text{ ft}^3$	1		26.00/ft <sup>3</sup>	9,568	10
	Castable 20 $V=184 \text{ ft}^3$	1		26.00/ft <sup>3</sup>	4,784	5
	Calcium Silicate $V=73.6 \text{ ft}^3$	1		22.75/ft <sup>3</sup>	1,674	2
			Total Pounds			
			84,888			87

COST ESTIMATE  
FOR  
ITOH CERAMIC  
RECUPERATIVE HEATER

PROJECT TITLE: CONCEPTUAL DESIGN OF ITOH  
FOR OPEN-CYCLE MHD POWER PLANT  
FLUIDYNE JOB NO.: 1296

SHEET 9 OF 16

DATE: July 1981

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SHEET NO.	DESCRIPTION	QTY.	WEIGHT	UNIT OF MEASURE	UNIT PRICE	TOTALS (\$000)
	MHD Gas Out Manifold 3/8 Wall					
	Steel $\rho=500 \text{ lb/ft}^3$					
	A=20,327 $\text{ft}^2$					
	V=635 + 10% (Stiffeners)					
	V=699 $\text{ft}^3$					
	Mat'l	1	349.500	\$ .35/lb	\$ 122.325	123
	Labor	1		1.25/lb	436.875	437
	Insulation Materials					
	KS-4 $\rho=121 \text{ lb/ft}^3$	1	512.410	.28/lb	143.475	144
	Castable 20 $\rho=36 \text{ lb/ft}^3$	1	76.226	.60/lb	45.736	46
	Calcium Silicate $\rho=46 \text{ lb/ft}^3$	1	38.960	1.05/lb	40.908	41
	Insulation Installation					
	KS-4 V=4.235 $\text{ft}^3$	1		26.00/ft	110.110	111
	Castable 20 V=2.117 $\text{ft}^3$	1		26.00/ft	55.042	55
	Calcium Silicate V=847 $\text{ft}^3$	1		22.75/ft	19,269	20
			Total Pounds			
			977,096			977



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**SHEET 10 OF 16**

DATE: July 1981

186

### RECUPERATIVE HEATER

## CONCEPTUAL DESIGN OF ITOH FOR OPEN-CYCLE MHD POWER PLANT

FLUIDYNE JOB NO.: 1296

**SHEET 11 OF 16**

DATE: July 1981

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SHEET NO.	DESCRIPTION	QTY.	WEIGHT	UNIT OF MEASURE	UNIT PRICE	TOTALS (\$000)
	Oxidant In Manifold					
	D=38.5", 3/8 Wall					
	A=2,560 ft <sup>2</sup>					
	V=80 ft <sup>3</sup>					
	Steel Q=500 lb/ft <sup>3</sup>					
	Mat'l	1	40.000	s 35/lb	14.000	14
	Labor	1		1.25/lb	50.000	50
	Insulation Material					
	Calcium Silicate Q=46 lb/ft <sup>3</sup>	1	4.907	1.05/lb	5.152	6
	Insulation Installation					
	Calcium Silicate V=107 ft <sup>3</sup>	1		22.75/lb	2.434	3
			Total Pounds			
			44,907			73

COST ESTIMATE  
FOR  
ITOH CERAMIC  
RECUPERATIVE HEATER

PROJECT TITLE: CONCEPTUAL DESIGN OF ITOH  
FOR OPEN-CYCLE MHD POWER PLANT  
FLUIDYNE JOB NO.: 1296

SHEET 12 OF 16  
DATE: July 1981

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SHEET NO.	DESCRIPTION	QTY.	WEIGHT	UNIT OF MEASURE	UNIT PRICE	TOTALS (\$000)
	Oxidant Out Duct					
	D=89.5, 3/8 Wall					
	A=1,885 ft <sup>2</sup>					
	V=58.9 ft <sup>3</sup>					
	Steel $\rho=500$ lb/ft <sup>3</sup>					
	Mat'l	1	29,453	\$ .35/lb	10,309	11
	Labor	1		1.25/lb	36.816	37
	Insulation Materials					
	KS-4 $\rho=121$ lb/ft <sup>3</sup>	1	47,518	.28/lb	13,305	14
	Castable 20 $\rho=36$ lb/ft <sup>3</sup>	1	15,552	.60/lb	9,331	10
	Calcium Silicate $\rho=46$ lb/ft <sup>3</sup>	1	3,613	1.05/lb	3,794	4
	Insulation Installation					
	KS-4 V=393 ft <sup>3</sup>	1		26.00/ft	10,218	11
	Castable 20 V=432 ft <sup>3</sup>	1		26.00/ft	11,232	12
	Calcium Silicate V=78.5 ft <sup>3</sup>	1		22.75/ft	1,786	2
			Total Pounds			
			96,136			101



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DATE: July 1981

190

COST ESTIMATE  
FOR  
ITOH CERAMIC  
RECUPERATIVE HEATER

PROJECT TITLE: CONCEPTUAL DESIGN OF ITOH  
FOR OPEN-CYCLE MHD POWER PLANT  
FLUIDYNE JOB NO.: 1296

SHEET 15 OF 16

DATE: July 1981

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SHEET NO.	DESCRIPTION	QTY.	WEIGHT	UNIT OF MEASURE	UNIT PRICE	TOTALS (\$000)
	Expansion Joints					
	Oxidant In Lines (38" DIA)	20		As Noted*	6,000	120
	Oxidant Out Lines (40" DIA)	20		As Noted*	6,000	120
	Headers to Manifolds (12" DIA)	80		As Noted*	1,000	80
	Miscellaneous Parts					
	Ceramic Pipe to Metal Pipe Clamps	80			250 ea.	20
	Ceramic Pipe to Metal Pipe Seals	80			100 ea.	8
	*Scaled from earlier quotes.					
						348

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DATE: July 1981

192

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9. Performing Organization Name and Address Burns and Roe, Inc. 185 Crossways Park Drive Woodbury, New York 11797				10. Work Unit No.	
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				14. Sponsoring Agency Report No. DOE/NASA/0107-3	
15. Supplementary Notes Final report prepared under Interagency Agreement DE-AI01-77ET10769. Project Manager, Henri Rigo and Task Engineer, Paul Penko, MHD-ETF Systems Office, NASA-Lewis Research Center, Cleveland, Ohio 44135					
16. Abstract  This report presents the results of an investigation into the use of three types of directly-fired ceramic heaters for preheating oxygen-enriched air to an intermediate temperature of 1144K (1600 F). The three types of ceramic heaters are: a) a fixed-bed, periodic flow ceramic brick regenerative heater, b) a ceramic tube and shell recuperative heater, and c) a moving bed ceramic pebble regenerative heater. Conceptual designs and cost estimates for heater types (a) and (b) and an engineering assessment of heater type (c) are presented for conditions in which the particulate matter in the MHD exhaust gas is in the dry powder state. A qualitative evaluation of the heater design, performance and operating characteristics under conditions in which the particulate matter is not solidified is also presented. The report also includes a comparison and overall evaluation of the three types of ceramic heaters and presents the results of an investigation to determine the temperature range at which the particulate matter in the MHD exhaust gas is estimated to be a dry powder.					
17. Key Words (Suggested by Author(s)) Magnetohydrodynamics power generation; Oxygen enrichment; Intermediate temperature oxidant heater; Ceramic heat exchanger			18. Distribution Statement Unclassified -- unlimited STAR Category 44 DOE Category UC-90g		
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of Pages 201	
				22. Price	

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combustor, would be required if liquid particulate matter enters the tube bundle. If a radiant section were added to cool the MHD gas upstream of the tube bundle, provision for removal of at least some seed material in this section would be required. If recirculation of the MHD gas were used, the necessary valves, mixers, and controllers would also be required.

Due to the added complexity of the system, and the increased likelihood of ceramic tube failure if spinel tubes were used, maintenance requirements would be expected to increase.

### 5.2.3 Moving Bed Regenerative Heater

The meandering or labyrinth type flow path required of the MHD gas in this case will certainly result in accumulation of seed material on the moving pebbles. In view of the difficulty envisioned in promoting proper pebble movement even without the added complexity of accumulation of seed material, this additional factor poses a serious concern as to the technical feasibility of using a moving pebble bed heater in this case. However, the fact that all of the pebbles are physically removed from the heater vessels and are thus accessible for continuous cleaning may mitigate this concern and make the moving pebble bed viable in the liquid particulate case.

The various aspects involved in adapting the moving pebble bed heater to the liquid particulate case are discussed in the following.

#### Materials

Magnesia alumina spinel pebbles and spinel castable materials or bricks for duct liners, vessels and lock hopper valve linings, and other components of the heater system should be acceptable for use to prevent corrosion from potassium compounds. Sufficient strength and abrasion resistance should be achievable but the cost of these materials will be higher than materials which would be satisfactory in the absence of liquid particulate.

